AMSAT
RADIO AMATEUR SATELLITE CORPORATION

PROCEEDINGS OF THE
AMSAT-NA

34th Space Symposium and
AMSAT-NA Annual Meeting

November 10-14
2016
aboard the
Carnival Liberty
Cruise Ship
Galveston, Texas

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Printed in USA

First Edition

TABLE OF CONTENTS

Welcome - Barry Baines WD4ASW..... i

Silent Keys..... ii

Section A: Satellite Technology

Adaptive Coding and Modulation for Phase 4 Ground
Michelle Thompson W5NYV..... 1

Designing a Ground Station for P4 and P5 Satellites
John P. Toscano, WØJT/5..... 13

Using DVB-S2X and Annex M to implement low cost Phase 4B Earth Station Terminals
Wallace Ritchie, WU1Y..... 25

AMSAT Goes to the Moon with the Cube Quest Challenge
Howie DeFelice AB2S..... 33

ASCENT AMSAT's Skunkworks
Bill Tynan, W3XO..... 39

Finding Veronica: Methods for Obtaining Recordings of Satellite Passes and Searching for Fox-1 Satellite Telemetry Beacons using Known Noise on an FM demodulated downlink
Douglas D. Quagliana, KA2UPW/5..... 45

Section B: AMSAT Fox-1 Systems Engineering Documentation – by the AMSAT FOX Engineering Team

AMSAT Engineering Documentation Update
Jerry Buxton NØJY..... 55

AMSAT Fox-1B (RadFxSat)

IHU to Experiment 1 Interface Control Document..... 57

Fox-1 Bus Pin Assignment..... 73

Fox-1B PCB-Stack..... 85

AMSAT Fox-1C (Fox-1 Cliff)

Camera resolution factors..... 87

AMSAT Fox-1E (RadFxSat 2)

System Requirements Specification..... 95

Downlink Specification..... 105

Fox 1-E Linear Transponder Average Power Tracking..... 123

Fox 1-E Mixers and IF circuit diagram..... 129

Fox 1-E 1200 BPS BPSK modulator..... 131

Heimdallr Lunar CubeQuest Challenge

Lunar ham transponder Link Budget 137

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Welcome on Board *Carnival Liberty*!

It is with great pleasure that I personally welcome you to the 2016 AMSAT Annual Meeting and Space Symposium @ Sea. This is our 34rd Space Symposium, reflecting a long tradition (started in the early 1980's) to provide an annual forum for amateur satellite enthusiasts to gather and share their ideas. AMSAT is proud of the technical content of the papers presented over the years reflecting the inventiveness of our volunteers and the significant contribution of presenters to "advance the radio art."

Holding our Symposium on board a cruise ship this year is a new experience. It offers not only a new venue that has attracted attendees from all over the world, but also signifies the international nature of amateur satellite communications. The launch of Fox-1A (AO-85) one year ago opened a new chapter in AMSAT's distinguished history of technical accomplishment and innovation, the first of a new class of CubeSats that provides amateur radio capabilities in a smaller housing as well as a platform for student and university-sponsored research. Education and science provides the justification for NASA to offer AMSAT launch opportunities. The success of Fox-1A has opened doors for AMSAT to extended collaboration with universities, culminating with RadFxSat-2/Fox-1E being selected by NASA this past February as our latest ELaNa (Educational Launch of Nano-Satellites) entry. Fox-1E is currently assigned to the ELaNa-XX launch which is expected to fly in December 2017 and will be our fifth 1U CubeSat. Unlike its predecessors, Fox-1E will feature a Mode J linear transponder. Fox-1Cliff and Fox-1D feature an L-Band uplink that has been added to the two-meter uplink initially flown on Fox-1A as well as a camera system developed by students at Virginia Tech. All four of the new Fox-1 CubeSats use a newly-designed MPPT (Maximum Power Point Tracker) board to manage power generation.

Meanwhile, Fox-1Cliff and Fox-1D ready to be shipped to Spaceflight, Inc. once SpaceX announces their revised launch schedule and is ready to accept our satellites. RadFxSat-1/Fox-1B completed its environmental testing in mid-October and is also ready for delivery early next year in anticipation of the ELaNa-XIV launch expected in March 2017. Congratulations to our engineering team as our volunteers have spent countless hours

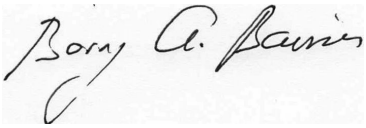
making our dream of keeping Amateur Radio in Space a reality. Our spacecraft allow students to design and build scientific payloads that enhance the level of basic scientific research, with the resulting payload data available to all.

As is AMSAT's tradition, this edition of the Proceedings contains updated details about the Fox-1 satellite design in addition to some of the details about the Heimdallr/Phase 5 communications design that we're placing in the public domain through formal publication. We're releasing these materials so that we may openly discuss our spacecraft development efforts in public as well as our desire to encourage greater use of amateur radio in space and to provide a foundation for other institutions to utilize our design. "An OSCAR in every university cubesat" will enhance amateur radio's presence in space while supporting scientific payloads.

Meanwhile, the 34th AMSAT Space Symposium provides an opportunity to discuss our next generation of projects, including development of the AMSAT Ground Terminal design that will support both GEO and High Earth Orbit operations as well as reaching out to greater distances with Phase 5. Our collaboration with Virginia Tech will hopefully result in a geosynchronous payload opportunity, though at this point it isn't clear what the prospects are for the primary payload. The Heimdallr/Phase 5 collaboration with Ragnorok Industries offers a potential mission to trans-lunar orbit, but NASA will not be making its selections until 2017.

After forty-seven years, we continue to develop remarkable satellites with educational outreach and scientific benefit that provides the basis for fulfilling AMSAT's mission. Your support will help to ensure a bright future.

73,



Barry A. Baines, WD4ASW
President

In Memory of Robert J. (Bob) Carpenter, W3OTC

Bob, a longtime friend, one-time business partner and devoted AMAST volunteer became a Silent Key Friday, January 8th, 2016.

Bob was born July 31,1930 in Washington, DC. I first met Bob in the late 1940s on six meters. At the time, we both lived in Silver Spring, Maryland. After a few QSOs we decided to meet and compare notes. I found that, in addition to the interest we shared in the VHF bands, he was very intrigued with FM broadcasting, as I had been for years.

Following graduation from The University of Maryland, in 1951 with a degree of Bachelor of Science in Electrical Engineering, Bob served in the U.S. Air Force, at the US Air Force Research Center in Cambridge, Massachusetts. On completing his Air Force commitment, he joined the Johns Hopkins Applied Physics Laboratory in the DC area where I was employed. Leaving the Laboratory 1955, Bob joined what was then called the National Bureau of Standards, first in Boulder, Colorado and later at their facility at Gaithersburg, Maryland. In his early work at the Bureau, he was instrumental in the development of technology for passing message traffic via the short bursts of VHF frequency propagation caused by the ionization produced by meteors entering the Earth's atmosphere. When Bob returned to Maryland he was involved in development of computer networking, retiring from what is now called The National Institute for Standard and Technology in 1992. In 1988, he received the US Department of Commerce Gold Medal Award for Distinguished Service.

Following retirement from NIST, Bob became available to assist AMSAT, of which he was an early member, holding AMSAT Life Membership Number 21. His knowledge of computers, was invaluable to Martha in keeping the office computers up to date and the various data bases current. He regularly came into the AMSAT office up until the last few days of his life.

Bob was active on six meters up until the time he sold his home in Rockville, Maryland and moved to a retirement facility in nearby Gaithersburg.

In earlier years, Bob did extensive traveling in Europe and elsewhere, his favorite country to visit being France. He became quite fluent in the French language. He went on one DXpedition, journeying to the French Caribbean island of Guadalupe. I, and a number of other six meter operators, were able to work a new country through Bob's efforts.

As mentioned earlier, Bob and I shared in interest in FM broadcasting. That interest blossomed during the late 1950s when Bob rented half of the house I then owned in Rockville, Maryland. After much discussion of the pros and cons, we decided to construct a station of our own. So, we applied for a Construction Permit (CP) from FCC to build a station in Bethesda, Maryland, a nearby suburb of Washington. Bob handled most of the technical work, while I concentrated on the business side. He always has been more adept at the technical side of radio and electronics than I. After receiving our CP, we went to work in earnest to build the station. Finally, in June, 1961, FCC came out with standards for broadcasting stereo. Bob and I reasoned that for a new station such as ours to have any chance of success, it had to hit the air with stereo. Since there was no stereo broadcasting equipment available at the time, much of what we needed had to be constructed by us This herculean task could not have been completed without Bob's expertise, but on November 12, 1961, only five months after FCC's establishment of standards for stereo broadcasting, WHFS, the DC area's first stereo FM station, hit the air on 102.3 MHz.

Once on the air, Bob kept WHFS on the air while I struggled with the multitude of paperwork associated with running a small business, especially a radio station. Each of us was smart enough to keep our "day jobs," making running a radio station especially difficult. We sold the station in 1963, affording Bob and me more time for ham radio.

It has been a great pleasure to have known Bob all these years. I will miss him and I know that Martha and all of AMSAT will miss him as well.

73 Bob

Bill Tynan, W3XO

With thanks to Perry Klein, W3PK, and Tom Pyke, K4DSD, who were responsible for providing valuable information for this tribute to Bob.

Doug Loughmiller, W5BL, of McKinney, Texas, passed away at age 60 on July 22, 2016. Doug served as AMSAT's president from 1988 to 1991, and also as editor of the AMSAT Journal. He was an active Amateur Radio instructor and was the recipient of the 2008 Herb S. Brier Award bestowed by the ARRL to recognize a volunteer Amateur Radio instructor. Doug was often asked to share his knowledge of ham radio and satellite operations, which he was comfortable doing in either large crowd settings or as a private tutor and mentor to smaller groups. He was an ARRL Life Member and a member of the Denton County Amateur Radio Association and the Red River Valley Amateur Radio Club, where he served as president in the 1980s.

Doug was probably best known in recent years as a high-altitude Amateur Radio balloon enthusiast, and he evangelized on that topic at the ARRL Centennial Convention in 2014 as well as at the Dayton Hamvention. He was the co-moderator of the BalloonSat Forum at Hamvention, and the co-founder of ARBONET (Amateur Radio Balloon over North East Texas) — described as “a poor man’s space program.” He also held a pilot’s license and was interested in motor sports, fishing, and scuba diving.

Doug grew up in Indiana and, after graduating from high school there, he attended Paris Junior College in Texas. His first career was as a baker, but from there he jumped to a job as a payload supervisor in the Satellite Communications Department at the University of Surrey in England. Subsequently he pursued a successful career in the electronics component industry, working for Arrow Electronics, Future Electronics/FAI, and RAM Electronic Sales.

A service was held in Paris, Texas, on July 27, with many AMSAT, ARRL, and amateur radio friends in attendance. Doug is survived by his wife Danielle, two brothers, Deane and Dale, and his loving canine companions LeRoy and Boudreaux.

Adaptive Coding and Modulation for Phase 4 Ground

Michelle Thompson W5NYV
Phase 4 Ground Lead

Phase 4 Ground provides digital radio solutions for any payload that complies with the Phase 4 Ground Air Interface document. These projects currently include but are not limited to Phase 4B Payload, Cube Quest Challenge (CQC), Phase 3E, and terrestrial Groundsats.

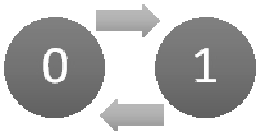
An Introduction to Coding and Modulation

In analog wireless communications, continuously varying signals are sent from transmitter to receiver. Voice, for example, is directly encoded in an analog transmission by a proportional relationship between baseband and carrier. The changes in audio that make speech intelligible to the ear are proportional to changes in either the frequency (FM), amplitude (AM), or phase (PM) of a transmitted carrier signal.

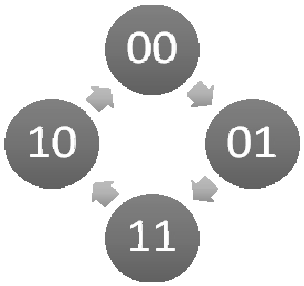
In digital wireless communications, data such as voice is represented by the digital symbols 1 and 0. Coding is the process of removing unnecessary redundancy in a signal and adding the right type of redundancy. Removing unnecessary redundancy is compression. Adding useful redundancy is channel coding. The type of channel coding we're most interested in is forward error correction coding. This is a way of coding the data where we can recover corrupted parts of the signal.

When we talk about **code rate**, we are talking about the ratio of how many bits go in to the forward error correction coder, or **encoder**, over how many go out. A rate 2/3 code takes in two bits and produces three. The extra bit is produced with mathematics especially designed to make the signal more durable as it travels from transmitter to receiver. The more bits you add, the smaller the ratio. Rates up to 1/9 are common. For a rate 1/9 code, for every bit that goes into the encoder, nine come out. As you'd expect, the more coding, the more durable the transmitted bits are against noise and interference. However, there's a cost. If you compare two signals that are transmitted at the same rate, the one with more extra bits to protect it needs more time to get through. The data rate is lower. It takes longer to transmit the same amount of data.

After the data is channel coded, the resulting bits are transmitted. The simplest type of digital waveform has two distinct states. One state corresponds to a 1, and the other state corresponds to a 0. Each of these ready-to-transmit-values is called a **symbol**. When we send one bit at a time, we have two symbols to choose from. An example of this type of modulation is Binary Phase Shift Keying (BPSK). The **modulation order** is the number of symbols we have to choose from. For BPSK it's two.



This simple BPSK modulation scheme can be dramatically improved. Sending one bit at a time is a great start, but we can do a lot better. If we use four distinct states in our transmitted waveform, then we can send binary data two bits at a time. We now have four symbols instead of two. An example of this type of modulation is Quadrature Phase Shift Keying (QPSK). The modulation order has doubled to four.



How about 8? 16? 32? Yes, to all, and more, all the way up to 256, 512, and even 1024! Sending 1024 bits in a single sample sounds amazing. So, why don't we just send 1024 bits in a single sample all the time?

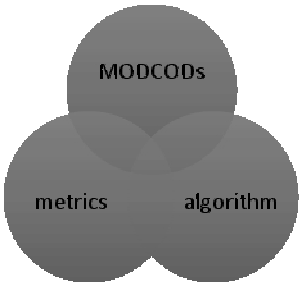
Engineering is all about trade-offs, and there's another one right here in front of us. The higher the modulation order the more power required. This means that the signal carrier power for transmitting two bits at a time must be twice that of transmitting one bit at a time, assuming that we are transmitting at the same **symbol rate**. We pay for the doubling in information capacity by having to provide double the power. As long as you have enough power, you can use more powerful modulations. If you have too much noise or not enough power, then you have to drop down to a lower modulation order.

Coding and Modulation Techniques in DVB

Traditional communications design assigns a fixed **mod**ulation and forward error correction **cod**ing (MODCOD) to a link. The MODCOD is selected to provide reliable communications under worst case conditions. For example, a microwave link that points down off a mountain is often designed to be good enough to work through rain fade and summer foliage. During clear conditions in the fall with no leaves, plenty of excess link margin is available, but a fixed system designed to work through summer thunderstorms cannot take advantage of this margin. In the Digital Video Broadcasting (DVB) world, this technique is called Constant Coding and Modulation (CCM). Phase 4 Ground uses many DVB protocols and techniques due to their high quality and widespread use in industry. Adapting these protocols to amateur radio is part of our mission.

Since it makes sense to adjust our link to better match observed conditions, one can design a system that uses a variety of MODCODs. An operator can then observe the link and then adjust the MODCOD to take advantage of better conditions. This technique is called Variable Coding and Modulation (VCM). VCM requires intervention of some sort to accomplish. In general, there is no feedback path from the receiver to the transmitter and a human is involved. But what if there was a feedback path from the receiver to the transmitter?

Adaptive Coding and Modulation (ACM) is a technique where the modulation and forward error correction are automatically changed in response to link conditions. As the link improves, higher order modulations and less coding allows increased throughput. Throughput can increase to take better advantage of available link margin.
Challenging link conditions are responded to by lower order modulation and more coding. The throughput will decrease, but the link is maintained. The adaptation is enabled by establishing the set of MODCODs to be used, listing the metrics that control the decision to change MODCODs, and defining the algorithm that produces the decision. These three ingredients make up ACM.



With a CCM systems, severe fades can cause total loss of the link and zero throughput. VCM can address some of the challenges of severe fades, but ACM automatically turns fade margin directly

into capacity. Maximizing throughput is highest with ACM.

Adaptive Coding and Modulation in Phase 4 Ground

The first challenge to an amateur-radio-centric version of ACM is that all existing implementations of ACM are proprietary. ACM is used in landline modems, 802.11, terrestrial microwave communications, and satellite links. When you are making money with subscribers, leaving margin on the table is not ideal. More efficient links mean more capacity, and more capacity means more subscribers, and more subscribers means more profit.

Most commercial ACM links generally only connect amongst themselves. There is no reason to create and maintain an open standard. Therefore, outside of the limited advice given in the implementation guidelines for DVB and a few white papers from a few companies, there is no open standard for ACM that we can simply adopt. For Phase 4 Ground we have to develop our own implementation of ACM, document it fully, and adjust it as we learn more in the field.

This is a great opportunity for amateur radio. Documenting the engineering trade-offs made in an advanced digital wireless system provides enormous educational opportunity for a wide variety of people, from interested amateurs to engineering students to satellite startups to people interested in machine learning and cognitive radio. Providing a working open-source implementation of ACM that other amateur projects can consider for adoption is a valuable engineering service.

The particular radio problem that has to be solved for space payloads is relatively straightforward. The geostationary and lunar and beyond radio environments are well-characterized. The available modulation schemes and coding rates are drawn from an established set described in the DVB standards (freely available from https://www.dvb.org). Advice from commercial and academic sources exist.

The particular radio problem that has to be solved for terrestrial Groundsats is also relatively straightforward. Groundsats are terrestrial versions of space-based payloads. They provide all the functions of an orbiting platform, but are on the ground. The control loop for terrestrial ACM has to be able to respond faster than for space. This is still well-characterized and advice exists from commercial and academic sources.

DVB allows an extreme resolution of MODCODs. Each and every frame can have a different MODCOD. This enables a link to respond very rapidly. For receiving transmissions from space, rapidly changing links are not the norm. The primary challenge is weather and rain fade or dishes not quite pointed right. For terrestrial links, changes in link quality can be more rapid, especially if the station is mobile. Terrestrial links have multipath, obstacles, noise, signal interference, and can also have rain fade and pointing problems.

There is a simple equation for ACM. In DVB, and for ACM in particular, the symbol rate is fixed. This greatly simplifies the communications system design. After a symbol rate is determined, a set of MODCODs is selected. The bit rate expression is therefore

Bit rate = symbol rate * modulation order * code rate

There are a lot of MODCODs to choose from in DVB. For space projects, the DVB-S family is the standard to reference. For terrestrial, we look to DVB-T. S stands for Space, and T stands for Terrestrial (think “television”).

Phase 4 Ground uses DVB-S2X and DVB-T2. The 2 in DVB-S2X and DVB-T2 stands for second generation. Second generation DVB-T2 and DVB-S2 is backwards compatible (with some effort) to the first generation DVB-S and DVB-T. Second generation standards provide substantial improvements over first generation.

DVB-S2X is an extension to DVB-S2 that provides additional MODCODS and some additional mechanisms. Of compelling interest to us is the additional MODCODs at the lower end of the spectrum that provide enhanced very low signal to noise (VL-SNR) operation. For CQC, VL-SNR operation will provide needed support. For Phase 4B Payload, VL-SNR allows for reasonably sized dishes and opens up the possibility of patch arrays.

A large advantage gained in choosing DVB standards is that the receiver is explicitly told, frame by frame, exactly what MODCOD has been chosen. The receiver does not have to do anything extra to use ACM. The complexity of ACM is in the transmitter.

The second challenge to an amateur-radio-centric version of ACM is that ACM assumes exactly one intended receiver. If the transmission is a QST or CQ, or intended for a roundtable talk group, or is merely open to monitoring by silent listeners, modifications to the standard ACM scheme will be needed.

Maximizing The Bit Rate

There is a very important distinction between analog and digital systems and how to interpret the guidance for best operating practices as set out in part 97.

In analog communications in amateur radio, there is a principle of conservation of power. The least amount of power should be used to ensure reliable communications in normal operations.

Part 97 : Sec. 97.313 Transmitter power standards

(a) An amateur station must use the minimum transmitter power necessary to carry out the desired communications.

Obviously, emergencies may require a different practice. In digital communications, the spirit of this guidance is best achieved with maximizing the bit rate, or throughput. Maximum bit rate ensures that the communications are achieved in the most efficient manner by providing maximum capacity. If this means transmitting at a higher power than is necessary to simply maintain a communications link, then so be it. It’s better to transmit for 450 milliseconds and then almost immediately allow someone else to then use the channel than to transmit for 450 seconds on minimum power using maximum coding and the lowest modulation scheme before relinquishing that particular channel. We equate bit rate with power and assert that this complies with the spirit of part 97.

We want to maximize throughput. This means maximizing the bit rate. In order to get to maximum bit rate, the professional advice is to start out with a stable link and work upwards. Here's an excerpt from Work Microwave's website.

> Start conservatively, approach the optimum: When setting up a link it is wise to start with very conservative settings to have a stable link running in the first place. Even if the "first shot" has not the desired bandwidth efficiency, an incremental approach will be the best way to optimize the link once it is up and stable. Due to numerous parameters and conditions affecting the Es/N0, the best settings will be reached by trial and error and can hardly be predicted beforehand.
>
> "ACM Dos and Don'ts." Work Microwave, 13 Mar. 2016, https://work-microwave.com/acm-dos-donts/

The Es/N0 value is a big clue. It's a critical metric for ACM. It stands for energy per symbol divided by the noise power spectral density. We already know what symbols are. A symbol is the distinct states of the modulator. The simplest one transmits 0 and 1. Two symbols are able to be transmitted so the modulation order is 2. Next most complex is 00, 01, 11, and 10. Four symbols are able to be transmitted so the modulation order is four. Next most complex is 000, 001, 010, 011, 100, 101, 110, 111. Eight symbols are available to be transmitted so the modulation order is eight. An example of this type of modulation scheme is 8PSK.

Energy Per Bit

Es/N0 is commonly used in the analysis of digital modulation schemes, but we're going to dig deeper and look at at a quantity called Eb/N0. This is the energy per bit divided by the noise power spectral density. Eb/N0 is the normalized signal to noise ratio of our link and this value is what drives the adaptation decisions in ACM. Think of Eb/N0 as the signal-to-noise (SNR) per bit. The energy per symbol and the energy per bit are related by the following expression.

$$Es/N0 = Eb/N0 * Log_2(\text{modulation order})$$

So for the modulations that we listed above, we have the following relationships.

$Es/N0 = Eb/N0 * Log_2(2)$ *two symbols to choose from*
$Es/N0 = Eb/N0 * Log_2(4)$ *four symbols to choose from*
$Es/N0 = Eb/N0 * Log_2(8)$ *eight symbols to choose from*

This gives us

For modulation order 2: $Es/N0 = Eb/N0$

The energy required to transmit a symbol of 0 or 1 is the same as required to transmit 0 or 1 bits. Makes sense!

For modulation order 4: $Es/N0 = Eb/N0 * 2$

The energy required to transmit a symbol of 00, 01, 10, or 11 is twice as much as required to transmit a 0 or 1. Still makes sense.

For modulation order 8: Es/N0 = Eb/N0 * 3

The energy required to transmit a symbol of 000, 001, 010, 011, 100, 101, 110, 111 is three times as much as required to transmit a 0 or 1. We are seeing the pattern.

In ACM, we have to be able to decide when we can afford to move on up to the higher order modulation schemes, which allows us to transmit more bits at once. If all the power we have available to us amounts to about as much power as required to transmit one bit, then we are stuck transmitting one bit at a time in BPSK. If our metrics tell us that we have more than three times the power required for a single bit available to us, then we can transmit a symbol that stands for three bits at once. We can go with 8PSK.

Within the modulation schemes are sets of coding rates. We've seen how spending power can increase the bit rate. How does coding fit in?

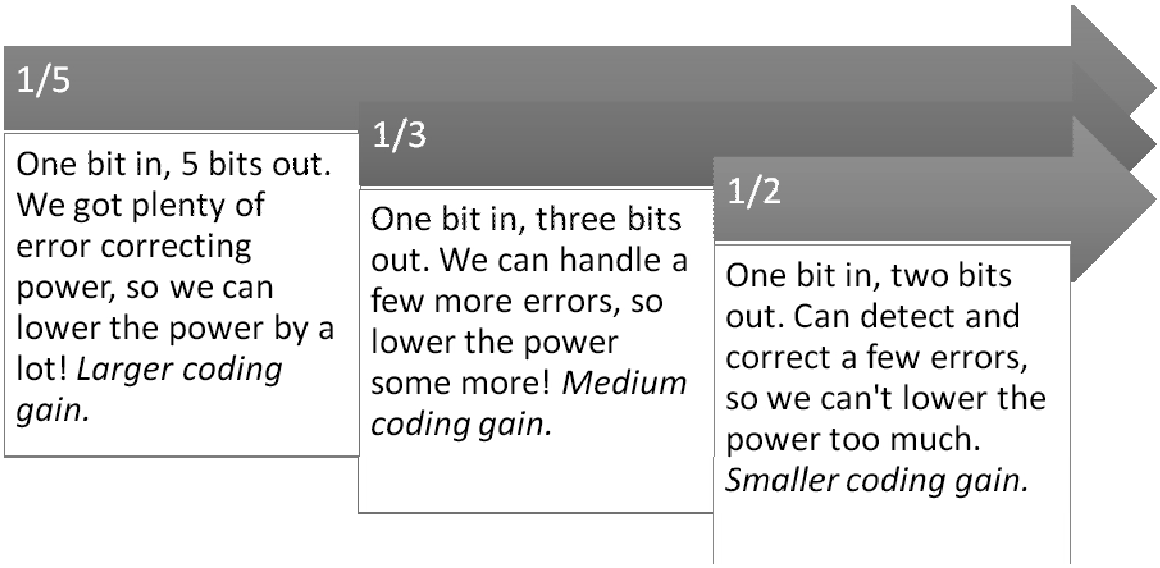
Coding Gain

There are two major types of coding. **Source coding** removes unnecessary redundancy so that source data can be more efficiently stored and handled. For example, digital music and video is source coded for compression. Otherwise the directly sampled files would be enormous.

Channel coding puts back in the right type of redundancy to make the transmitted signal resilient. Forward error correction puts in additional bits that allow for both the detection and correction of errors. Better than magic!

In DVB-S2X, the forward error correcting code is called LDPC-BCH. It's an advanced **concatenated block code**. Block code means that groups of bits are gathered up and then mathematically modified with extra bits. There are other types of codes that operate on continuous streams of bits. Those types of codes operate bit-by-bit as long as there are bits in the pipeline. Each block stands alone and is decoded separately. Concatenated means that two different codes are used. The reason these two different codes are used together in DVB-S2X is because using them together cancels out weaknesses. Taken together they make a very high-performance code.

Coding gain is the measure of the difference between the Eb/N0 levels of an uncoded system when compared to a coded system, when both systems are required to provide the same bit error rate. We have the same signal energy available in either case. Coded signals allow us to correct errors, which allows us to transmit at less power.


1/5
One bit in, 5 bits out. We got plenty of error correcting power, so we can lower the power by a lot! Larger coding gain.
1/3
One bit in, three bits out. We can handle a few more errors, so lower the power some more! Medium coding gain.
1/2
One bit in, two bits out. Can detect and correct a few errors, so we can't lower the power too much. Smaller coding gain.

What can with do with this extra gain? In ACM we can put it right to work in maintaining target bit error rate performance. If we know what Eb/N0 we need, and we know which codes consume that much Eb/N0 to maintain a particular performance level, then we are able to select the code that maximizes bit rate while minimizing bit error rate.

We do this by measuring Eb/N0 at the receiver. This tells us how strong the signal is. Eb/N0 is reported to the ACM controller, and the right modulation and coding is selected for that receiver. In commercial satellite, the ACM controller is centralized and is usually on the ground. For Phase 4B Payload and for Groundsats, it's planned that the controller will be onboard the satellite.

Changing the modulation is the coarse-grain control knob in ACM. Changing the code rate is the fine-grained control knob in ACM.

Putting Metrics, MODCODs, and Algorithms Together

For ACM to work, the modulator must send which MODCOD is being used at the start of each frame. The receiver must be able to handle an arbitrary change in MODCOD without any advance knowledge. The receiver must be able to work fast enough to process the packet or frame without corrupting or dropping it. This puts a lot of pressure on the receiver. This pressure can be alleviated in several ways. One example is using standardized mechanisms in DVB such as time slicing. See Wally Ritchie's paper "Using DVB-S2X and Annex M to implement low-cost Phase 4B Earth Station Terminals" for ideas on time slicing.

Another requirement is that the receiver needs to be able to measure or calculate an estimate of the link quality (Eb/N0) and then communicate this estimate to the payload. The payload must be able to process this reported metric and then adapt the data rate and change the MODCOD sent to the

receiver. This maximizes the data rate, complies with the spirit of part 97, and is sparkling with efficiency and style.

Reacting to changes in channel quality makes sense. But can there be additional improvement? Yes, there can! There's a large body of research that shows how throughput and bit error rate performance changes when using linear prediction to estimate the future state of the channel based on past measurements.

There are practical limits to how quickly an ACM system can respond. In general, about 1dB per second is achievable. If something happens and the demodulator comes unlocked, then it's a good idea to go back to the lowest MODCOD. This way, you're starting over with the highest probability of re-connecting and then working your way back up to maximum bit rate.

Assuming that the receiver has acquired the satellite and done all necessary chores to receive the downlink, and assuming the receiver has the necessary authentication, and assuming the receiver can successfully determine which channels are free for transmission to the payload, the receiver now needs to determine what MODCODs it is capable of receiving.

The dish might not be pointed correctly. The receiver might be a bit noisy. The local oscillator might not be rubidium quality. There might be some atmospheric conditions that attenuate the signal. Someone could have dented the dish. A connector could be loose. Some of these factors change very slowly over time, and some of them change more quickly. All of these factors affect receive capability and all of them can be automatically accommodated with ACM.

The standard model of ACM has the receiver monitor and report its Eb/N0 to the controller. In our case, the controller can be in the payload. When Eb/N0 falls below a setpoint, the receiving station is sent a lower MODCOD. The setpoints are configured to provide a minimum level of performance. When going to a lower MODCOD, throughput is reduced but the link is maintained. Eb/N0 reports can be part of the frame structure.

Digital communications performance can be defined by maximum allowable bit error rate. DVB is designed to provide very low error rates. The standard of performance for DVB is called quasi-error-free. DVB allows one uncorrected error per hour of video broadcast viewing. This is a very high standard that works out to a bit error rate of about $1*10^{-10}$ to $1*10^{-11}$.

When you establish the values for Eb/N0 that you're going to allow, they have to be made based on what bit error rate you can tolerate. Quasi-error-free bit error rate in DVB is many orders of magnitude lower than, say, the maximum bit error rate for GSM ($1*10^{-3}$) and lower than the data-centric maximum bit error rate for 3G data ($1*10^{-6}$). Voice is more forgiving than data which is more forgiving than digital video broadcasting. Selecting a baseline bit error rate of $1*10^{-6}$ is not out of line.

Once you have a bit error rate that you want to keep below, then you calculate a table of Eb/N0 values that would cause you to move to a better MODCOD. "Better" could mean higher or lower depending on whether you were doing great or having trouble with the link.

Anyone that's ever worked with set points knows that there's a potential for oscillating when the measured value is very close to the set point. A common approach with ACM is to put in 0.3dB or more of hysteresis. Going up requires a bit more SNR than coming down. This doesn't just prevent oscillating between two MODCODs but can also help maintain demodulation lock. You don't want your radio to work any harder than it has to.

We want the operator to see as much information about the metrics and the link as they desire. Our goal is to provide quality presentations of signal-to-noise ratios, states of lock, channel occupancy, system status, User synchronous log visualizations, symbol rate, modulation constellation, data rate, bit error rate, and more. Metrics such as these and more are presented by an application that can be run or not, depending on the preferences of the operator. Some systems provide a bit error rate tester as an application. This can help debug situations of synchronization loss, unexpected bursts of bit errors, or other problems. If the operator doesn't want to see any of this, then they don't have to. It should "just work" without intervention, and provide clear error or failure messages if anything goes wrong.

When a higher MODCOD is selected, the available data rate is increased. This usually isn't a problem. When a lower MODCOD is selected, the available data rate is decreased. This can be a problem. Congestion control must be considered and implemented to avoid losing packets or frames. Buffers and FIFOs to the rescue!

Is maximizing the bit rate enough? What about latency? While ACM considered in the abstract doesn't minimize or maximize latency, the use of DVB-S2X can offer some relief over DVB-S2. Latency will be one of the biggest challenges to operator experience on the Phase 4B Payload. It is impossible to go faster than the speed of light, and the round-trip delay of at least 240mS is substantial. There are things that we can do to mitigate latency such as reducing buffer size and using shorter frame lengths. Providing voice memo as an alternative to real-time voice is another.

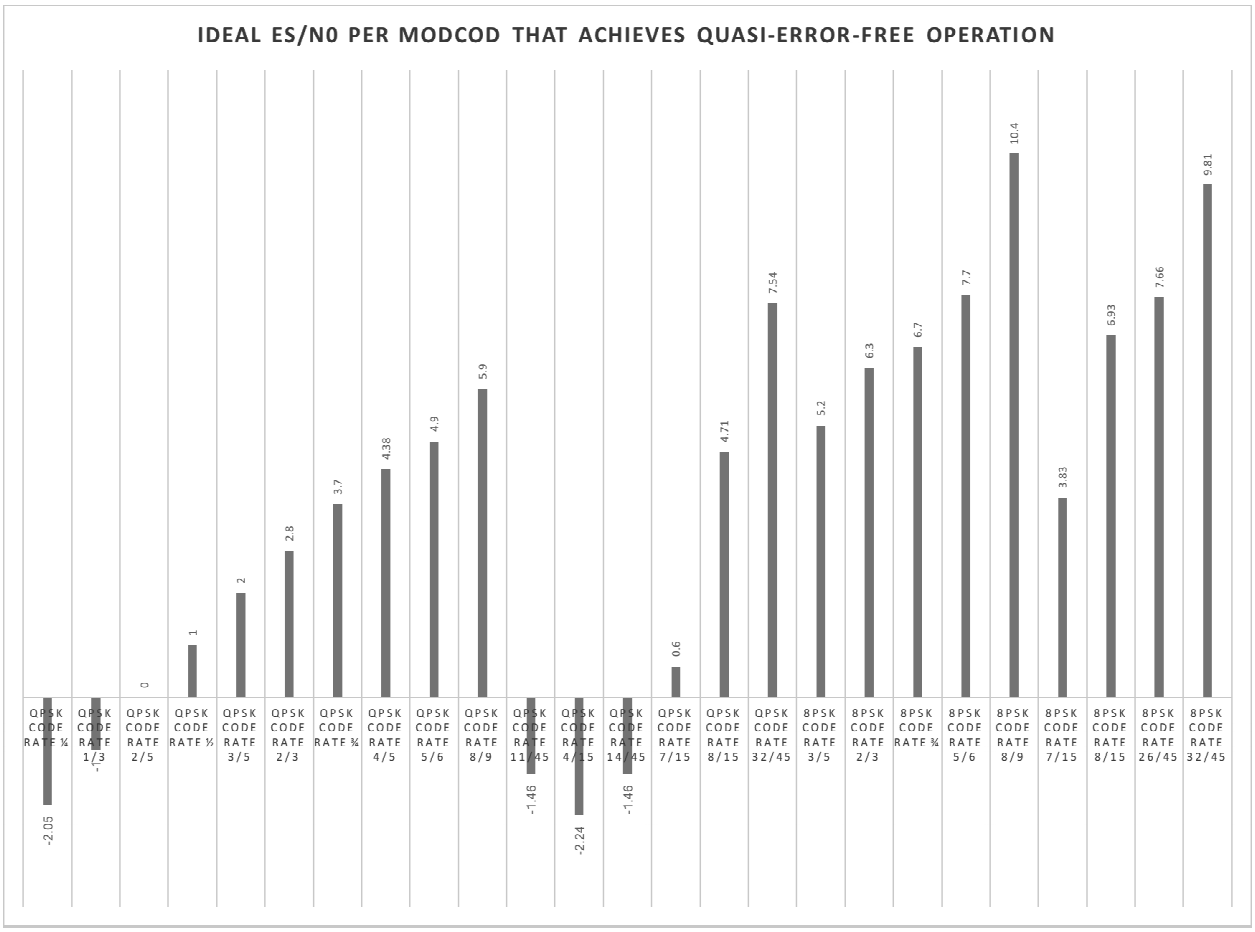
Proposed Adaptive Coding and Modulation Scheme

Here's the current proposal for MODCODs, metrics, and algorithm for ACM for Phase 4 Ground. This is an open design that is going into prototyping and testing. The expectation is that this proposal will be reviewed, refined, and retuned to maximize bitrate and avoid commonly encountered challenges. Some challenges are anticipated and have been mentioned above. Others we will certainly discover along the way.

There are choices of frame size in DVB-S2 and DVB-S2X. The CCSDS (Consultative Committee for Space Data Systems) RF Modulation and Channel Coding Workshop, among other individuals and groups, recommends the short frame size for near space-earth transmissions. A selection of the short frame size MODCODs that we believe will work best for Phase 4B Payload are presented in the table below. Short frame size is 16200 bits. Frame size and the presence or absence of pilot signals is communicated in the TYPE field of the physical layer header. Each MODCOD has an identification code. The decimal value of that code, which goes into the PLS field of the physical layer header, is the first column. Ideal Es/N0 is ideal energy per symbol divided by the noise power spectral density in dB in order to achieve a frame error rate of 10^{-5}. This is quasi-error-free operation with no impairments. In other words, very ideal!

PLS Code	MODCOD Name	Rate	Ideal Es/N0
1	QPSK code rate ¼	1/4	-2.05
2	QPSK code rate 1/3	1/3	-1.00
3	QPSK code rate 2/5	2/5	0
4	QPSK code rate ½	½	1
5	QPSK code rate 3/5	3/5	2
6	QPSK code rate 2/3	2/3	2.8
7	QPSK code rate ¾	¾	3.7
8	QPSK code rate 4/5	4/5	4.38
9	QPSK code rate 5/6	5/6	4.9
10	QPSK code rate 8/9	8/9	5.9
216	QPSK code rate 11/45	11/45	-1.46
218	QPSK code rate 4/15	4/15	-2.24
220	QPSK code rate 14/45	14/45	-1.46
222	QPSK code rate 7/15	7/15	0.60
224	QPSK code rate 8/15	8/15	4.71
226	QPSK code rate 32/45	32/45	7.54
12	8PSK code rate 3/5	3/5	5.2
13	8PSK code rate 2/3	2/3	6.3
14	8PSK code rate ¾	¾	6.7
15	8PSK code rate 5/6	5/6	7.7
16	8PSK code rate 8/9	8/9	10.4
228	8PSK code rate 7/15	7/15	3.83
230	8PSK code rate 8/15	8/15	6.93
232	8PSK code rate 26/45	26/45	7.66
234	8PSK code rate 32/45	32/45	9.81

When we look at a chart of these MODCODs, we can see the effect of modulation and coding. We get about 12dB of range just using QPSK and 8PSK. We haven't yet listed the VL-SNR codes that can bring the Es/N0 down to -10dB. They require some additional care and work to implement.



We need to select enough different MODCODs to give the performance we want, but not so many that we have a situation where the algorithm is flailing about making unnecessary changes. The starter list of MODCODs is the following. This gives a MODCOD at about every 2-3dB.

QPSK 4/15
QPSK 2/5
QPSK 4/5
8PSK 5/6
8PSK 8/9

All measurements have error. There are multiple sources of error and noise. The set of target Es/N0 (or Eb/N0) numbers need to be far enough apart to where link performance instead of noise is the main trigger of an ACM decision.

If three MODCODs turn out to be the best match, then it means we use three MODCODs. If we can use more, then we use more.

Once the MODCODs are selected, hysteresis is applied, and the metrics are monitored, then the choice of which MODCOD to apply to which frame can be usefully made.

While the underlying mechanism is straightforward, there are many problems to solve. Flow control and what type of quality of service needs to be decided. The DVB implementation guidelines give a great start for ACM and describe ways to set up Generic Stream Encapsulation (GSE) to help implement ACM.

This is where we stand today. We're writing policy management code in Python in order to simulate ACM. We are learning the details of how to create DVB frames and predict performance of the DVB physical layer components.

The next big step after the design, document, simulate, and test stage is to implement what works using GNU Radio with the USRPs donated by Ettus Research. This allows bench testing and then testing over the air as a Groundsat.

Want to help? You're welcome to join Phase 4 Ground!

Apply at http://www.amsat.org/?page_id=1096

For Phase 4 Ground, you do not have to be a US citizen.

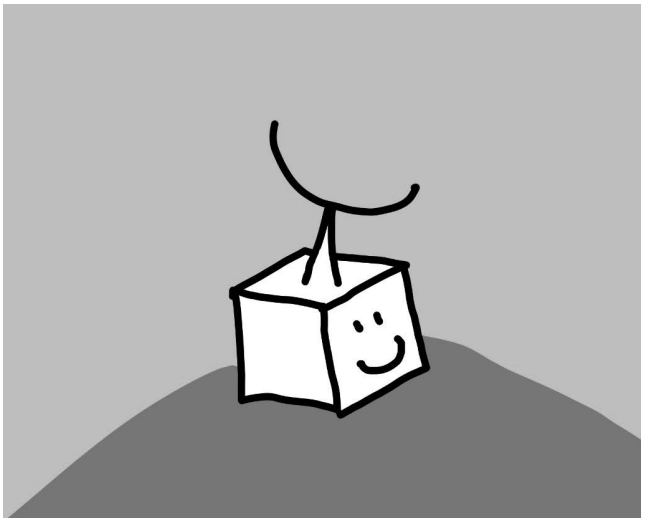
We have an announcement email list phase4@amsat.org
a Slack team at https://phase4ground.slack.com
and documentation at our GitHub https://github.com/phase4ground

There are about 100 people on the Phase 4 Ground email list, and 52 members on the Slack team, and about 50 on GitHub. Not all members are active on the project, and not all members are active in each phase.

There's an enormous variety of work available, from art design to antenna design. Our mission is to create an open, digital, modular microwave radio that is fun, teachable, and affordable, that will support terrestrial and space communications. You are welcome to join and contribute however you are able!

Designing a Ground Station for P4 and P5 Satellites

John P. Toscano, WØJT/5
Member, AMSAT ASCENT Skunkworks



This paper will describe some of the considerations that are going into the design of ground stations (ground terminals) for the upcoming P4 and P5 satellites.

Just to refresh your memory, let me mention briefly what P4 and P5 refer to.

Phase 4 or P4 or φ^4 refers to a satellite in Geosynchronous or Geostationary Orbit, about 36,000 Km above the surface of the Earth. AMSAT is partnering with several other entities to "rideshare", *i.e.,* to add an Amateur Radio package as a "piggyback" payload supplement to an existing satellite that is planned for Geosynchronous Orbit. Due to ITAR restrictions, this presentation will have fairly little to say about the details of the satellite itself. It will focus on the ground stations that Amateur Radio Operators will be using to access the satellite. Satellites in Geostationary Orbit, such as those used by commercial satellite TV broadcasters, have a period of revolution around the Earth which is the same as the rate at which the Earth itself is rotating underneath, giving the appearance that the satellite is hovering motionless in the sky. A Geosynchronous Orbit, on the other hand, is one where the satellite appears to trace a "Figure 8" pattern in the sky, and returns to the same sky position (azimuth and elevation) at the same time every day. Relatively small amounts of azimuth and elevation motion are needed during the course of a 24 hour period, and typically once your antenna is pointed correctly, it does not need to be re-positioned very frequently. The orbit can be selected to favor either the Northern or Southern hemisphere. Our rideshare for P4 is to Geosynchronous Orbit. In addition to the relatively small amount of re-positioning of antennas required, another advantage of GEO orbits is that the satellite "footprint" covers nearly an entire hemisphere of

the Earth at once. This means that if the satellite is positioned over the continental United States (as planned), Amateur radio operators throughout most of North and South America can all “see” it and work it, if they have the required equipment.

Phase 5 or P5 or φ^5 refers to a satellite in Lunar Orbit or beyond. AMSAT is working on a P5 satellite as part of the NASA-sponsored Cube Quest Challenge. This is a contest that is designed to stimulate innovation in small satellite technology by having the competitors work on solving the problems of operating small satellites far above the Earth’s surface, at distances where radio signals become very weak, navigation cannot rely on the Earth’s magnetic field or on GPS satellites, radiation exposure levels are much higher, etc. There is a separate presentation at this Symposium that discusses the CQC or Cube Quest Challenge in more detail. AMSAT is partnering with the Ragnarok Industries Nano-Satellite Company, on the development of an entry in this contest. AMSAT is providing the radio technology, while Ragnarok is designing the satellite spaceframe, propulsion, navigation, power generation, etc. Once the CQC is over, AMSAT will take possession of the 6U CubeSat in Lunar Orbit.

One property that P4 and P5 satellites will share is their much greater distance from the surface of the Earth than current amateur satellites. Therefore, some innovations in radio technology will be needed for optimum success in communicating through them. AMSAT has committed to designing ground station equipment for both P4 and P5 satellites.

We expect that *at least* 3 different designs for P4/P5 ground terminals will evolve:

1. A complete, ready-to-go system, ready to run “out of the box”, with no assembly required, for those Hams with more money than time or assembly skills.

2. An inexpensive terminal for budget conscious hams; possibly a complete kit containing all of the needed components, ready to be assembled by the Ham, or at least a detailed BOM (Bill Of Materials) for the Ham to use for sourcing his/her own parts.

3. A guide for those folks who wish to “roll their own” ground terminal, mostly from commonly available modules. The documentation that will be provided by Phase 4 Ground will be as full, helpful, and dynamic as possible, hoping to make the recipe section as challenging as following something from the Good Housekeeping Cookbook. In other words, not very.

At the time of this presentation (November, 2016), the specifics of the design implementation continue to evolve, however there are some attributes that have been decided upon with pretty good certainty, after considerable deliberation. Here are some of the things that we know (or at least that we *think* that we know) about the ground terminal design at this point in time:

1. The uplink from the ground stations to the satellites will be in the Amateur Satellite Sub-Band of the C Band, namely 5650-5670 MHz.

2. The downlink from the satellites to ground stations will be in the Amateur Satellite Sub-Band of the X band, namely 10450-10500 MHz.

3. The ground station will need one or two parabolic dish antennas. In a typical home station or homebrew station, using two dishes allows the 5 GHz uplink antenna to be easily positioned several feet away from the 10 GHz downlink antenna, which provides considerable protection of the downlink from desense by the uplink. For EMCOM applications, or for many portable setups in general, a single dish with a dual-band feed would be preferred, since there is less work needed to erect the station, only a single dish to point, etc. Current estimates are that a 1 meter diameter dish should be sufficient for P4, but a 1.8 meter diameter (or larger) dish is more likely to be needed for P5. AMSAT is attempting to design a dual-band cross-polarized feed horn to illuminate a parabolic dish, keeping as much isolation of the transmitter (C-Band) from the receiver (X-Band) as possible. A design goal of 100 dB or more of isolation is hoped for. If this does not succeed, an alternative plan being considered is a combination dish/patch antenna system.

4. There may be situations where direct (simplex) communication between one ground terminal and another is desirable. This is being planned for as an optional capability for selected ground terminals, which would have a full transceiver on X-band instead of only a receiver. Such terrestrial communication would likely occur in the 10440-10450 MHz sub-band which is designated for terrestrial broadband digital communication. These choices would comply with IARU regulations on the Amateur Satellite Service, and both FCC regulations and ARRL band plans for the Amateur Radio Service.

5. DVB-S2x modulation and demodulation of RF signals will be used for communications between a ground terminal and the P4 or P5 satellite. This is a relatively recent industry standard that has been very well-received in the satellite TV industry and seems to be a good fit for our digital data aspirations.

6. DVB-S2x VLSNR (Very Low Signal-to-Noise Ratio) modulation may also be needed, especially for P5. This satellite will be much further away from the surface of the Earth, causing greater path loss between the satellite and the ground station; and at the same time, since P5 will be squeezed into a 6U CubeSat, which is approximately the size of two reams of paper, its antennas will be smaller (have less gain) and its solar panels will be smaller (produce less DC power) so its X-band power amplifier will be lower in power output (weaker downlink signal). While the DVB-S2x VLSNR standard appears to be a good one, it has yet to gain much traction in the satellite TV industry, so this is an area where AMSAT is on the “bleeding edge” of implementing the technology, rather than depending on a plethora of COTS (Commercial, Off-The-Shelf) solutions to choose from.

7. For those ground terminals having the optional capability of terrestrial (non-satellite) simplex communication, DVB-T2 modulation will be used for that purpose. DVB-T2 is optimized for radio signals pointed at terrestrial stations (and subjected, for example, to multipath interference), instead of being pointed into the sky (where multipath interference should be non-existent).

8. Since we intend to pass a lot of different types of digital data, rather than only video signals, we will use a standard known as GSE or Generic Stream Encapsulation as a wrapper around the data packets. This has much less overhead than using the MPEG wrapper commonly used by satellite TV video streams, without precluding the transmission of television signals at all.

9. AMSAT plans to support *only* a digital transponder on these satellites with its ground terminal design. While it is possible that P5 could support a C/X analog transponder on a part-time, scheduled basis, using some of the circuitry planned as a failsafe backup system, there are no plans to incorporate this capability in an AMSAT ground terminal, so such operation would remain in the realm of well-equipped microwave EME stations who design and build their own ground station.

10. Both P4 and P5 will be launched with a SDR (Software-Defined Radio) Transponder. This will enable the RF channel specifications to be re-defined even after the satellites are launched. Naturally, that capability would be meaningless unless the ground terminals were also capable of re-definition to match. So the AMSAT ground stations will also use SDR technology, which will allow the Ham to “re-create the radio design” with a simple firmware download and installation.

Figure 1 is a block diagram showing the design of a typical, entry-level AMSAT ground station for the P4 and P5 satellites.

The ovals at the top left and top right of the drawing represent offset feed parabolic dishes, possibly discarded/re-purposed satellite TV dishes. The receiving dish’s feedhorn sends its signal through a bandpass filter (to eliminate as much out-of-band noise as possible, particularly the first harmonic of the transmitter signal) and then to a low-noise pre-amplifier, before being routed to the SDR receiver. It may be possible to substitute an inexpensive PLL-based COTS Satellite TV LNB for the feedhorn, filters, and preamp assembly for stations that will have X-band receive-only operation. This is discussed further, later in the paper. It should be pointed out that no existing SDR’s can directly receive X-band signals, so if the LNB solution is not being used, then a full transverter or at least a receive-converter will be needed to translate the X-band signals to a lower frequency that the SDR can handle.

The SDR transmitter is shown sending its output signal through filtering and then to power amplification hardware. All existing SDR’s produce too little RF power (on the order of only about 10 milliwatts) to make a useful satellite transmitter by themselves, and many of them are incapable of generating frequencies as high as C–band. Both problems can be addressed by

the use of a transverter on the output side, or at least a transmit converter, but if the chosen SDR is one that can reach C-band directly, then filtration and power amplification between the SDR and the dish feedhorn can be sufficient.

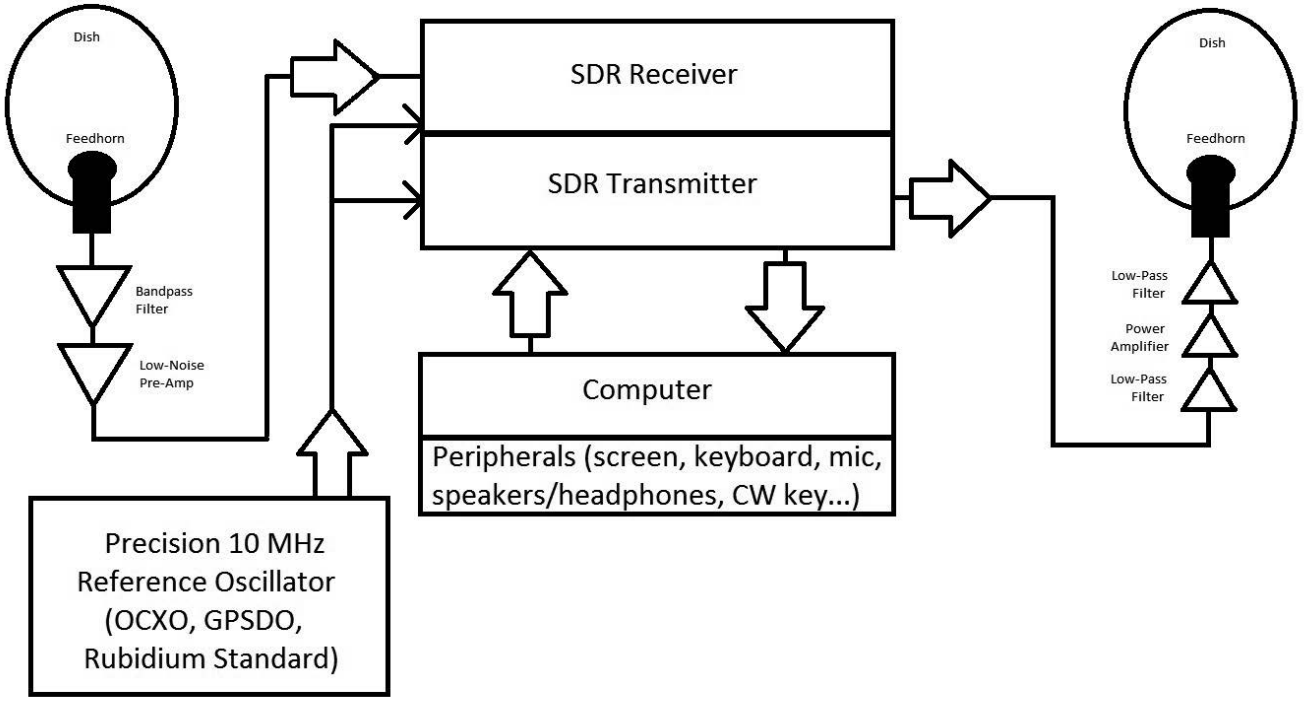


Figure 1: Block Diagram of a Typical Entry-Level AMSAT Ground Terminal for P4 and P5 Operations

Figure 1 shows the inclusion of a precision 10 MHz Reference Oscillator as part of the design. This is essential for ground stations that wish to participate in the CQC, because extremely precise frequency control is needed to perform ranging and velocity calculations that are needed for navigation of the 6U CubeSat into Lunar Orbit. It might be argued that a precision frequency standard is “only recommended” for working P4, but locking your SDR’s frequencies to a highly precise standard will make it easier to tune in to the satellite. Microwave operators have known for years that locking their radio systems to a precise frequency standard makes it far easier to tune to the actual frequency that you are trying to tune, in order to work another station that expects you at a particular frequency. An OCXO (Oven-Controlled Crystal Oscillator) can often be found at a reasonable price on the surplus market. A GPSDO (Global Positioning Satellite Disciplined Oscillator) is typically a TCXO (Temperature-Controlled Crystal Oscillator) or OCXO that provides higher precision by repeatedly adjusting its crystal oscillator to match the extremely precise Cesium standards on the constellation of GPS satellites. A rubidium standard can also be acquired on the surplus market for a bit more money, and is more precise than an OCXO, but less precise than a Cesium standard, so it too might be GPS-Disciplined. In any case, it is likely to need replacement sooner than a GPSDO if used heavily, because of aging of the internal rubidium standard.

Of course, Figure 1 also points out that a computer of some sort is going to be required to operate the SDR by running the specific software that defines how the radio works. We'll have a little more to say about that later in this paper.

This brings us to a discussion of the choice of SDR to use for the ground terminal. Your first idea might be to use the same SDR that is flying on the P4 and P5 satellites, to insure the maximum compatibility of hardware and software. So, what is the SDR flying on P4 and P5? It is the AstroSDR by Rincon Research Corporation, shown in Figure 2.

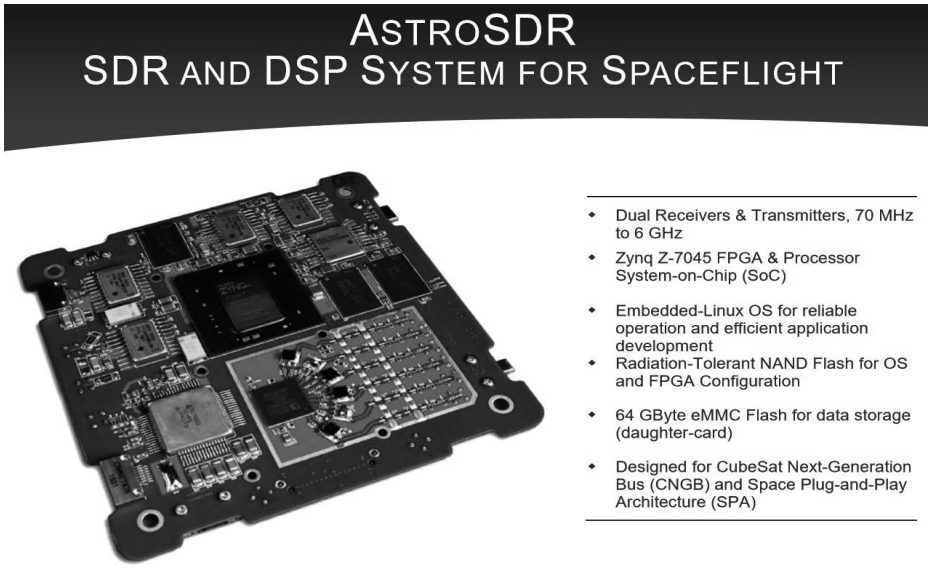

ASTROSDR
SDR AND DSP SYSTEM FOR SPACEFLIGHT
Dual Receivers & Transmitters, 70 MHz to 6 GHz
Zynq Z-7045 FPGA & Processor System-on-Chip (SoC)
Embedded-Linux OS for reliable operation and efficient application development
Radiation-Tolerant NAND Flash for OS and FPGA Configuration
64 GByte eMMC Flash for data storage (daughter-card)
Designed for CubeSat Next-Generation Bus (CNGB) and Space Plug-and-Play Architecture (SPA)

Figure 2: The AstroSDR Being Flown on P4 and P5 Satellites

The problem with using the AstroSDR for the ground station is cost. How expensive is it? As the expression goes, “If you have to ask how much it costs, you can’t afford it.” Remember that this SDR is designed to be tolerant of the high radiation levels and extreme temperature swings that will be encountered in high Earth Orbit or in Lunar Orbit, which is overkill for a ground station. We can use something much more affordable. Nevertheless, not just any SDR will do the job. Here are some of the capabilities that will be needed for the ground stations and which are not present in all possible SDR’s:

1. The ability to operate at C-Band and X-Band. If the SDR cannot reach these 5 and 10 GHz frequencies directly, then an additional up-converter and/or down-converter will be needed.

2. Full-Duplex operation, where the satellite’s downlink is received concurrently with the uplink transmission by the ground station. If the SDR cannot operate in Full-Duplex (simultaneous transmit and receive) mode, then a separate SDR might be used for each of the transmit and receive functions.

3. One early concept for the ground station SDR was to use a HackRF board as the 5 GHz transmitter SDR (this board is half-duplex only, but can operate directly up to 6 GHz), and an inexpensive RTL-SDR dongle plus a COTS satellite TV LNB for the receiver. The LNB would drop the frequency of the satellite downlink from around 10.5 GHz to around 600 or 700 MHz, well within the range covered by the RTL-SDR dongle. Unfortunately, the bandwidth of the RTL-SDR is far too narrow to work in our ground station.

4. Our early testing suggests that a high-speed I/O channel between the SDR's RF front end and the computer performing the DSP operations to encode and decode signals is needed. USB2 seems to be too slow. USB3 or Gigabit Ethernet might be needed. An FPGA (Field Programmable Gate Array) that is tightly coupled to the digital data stream could also work, but FPGA's are usually expensive and are more difficult to program than general-purpose microcomputers. This I/O limitation probably rules out the HackRF also.

Parameter	HackRF One HackRF Blue	Ettus B200	Ettus B210	BladeRF x40 or x115	RTL-SDR	LimeSDR
Frequency Range	1 MHz – 6 GHz	70 MHz – 6 GHz	70 MHz – 6 GHz	300 MHz – 3.8 GHz	22 MHz – 2.2 GHz	100 KHz – 3.8 GHz
RF Bandwidth	20 MHz	61.44 MHz	61.44 MHz	40 MHz	3.2 MHz	61.44 MHz
Sample Depth	8 bits	12 bits	12 bits	12 bits	8 bits	12 bits
Transmitters	1	1	2	1	0	2
Receivers	1	1	2	1	1	2
Duplex	Half	Full	Full	Full	N/A	Full
Interface	USB 2.0	USB 3.0	USB 3.0	USB 3.0	USB 2.0	USB 3.0
Program-mable Logic	64 cell CPLD	75K FPGA	100K FPGA	40K or 115K FPGA	N/A	40K FPGA
Chipset	MAX5864 MAX2837 RFFC5072	AD9364	AD9361	LMS6002M	RTL2832U	LMS7002M
Open Source?	Full	Schematic, Firmware	Schematic, Firmware	Schematic, Firmware	No	Full
Transmit Power	-10 dBm to +15 dBm	10 dBm+	10 dBm+	6 dBm	N/A	0-10 dBm
Price	$299.00	$686.00	$1,119.00	$420 or $650	~$10	$299.00

Table 1, adapted from the LimeSDR CrowdSource documents, summarizing salient features of 8 different SDR's that have received scrutiny by the ASCENT team.

As can be seen from Table 1, the SDR that comes closest to meeting all of the needs of a ground station is the Ettus B210. It can transmit in the 5.7 GHz C-Band, it is Full-Duplex, it uses USB 3.0 for its interface to the computer, and has a large FPGA that may be programmed to perform the difficult, time-consuming computations needed to encode and decode DVB signals. The main problem with the Ettus B210 is its price of $1,119. The LimeSDR is almost as capable, for about ¼ the price ($299 instead of $1,119). It cannot transmit in the 5.7 GHz C-Band without assistance, which is its main shortcoming for the P4/P5 ground terminal. But Lime Micro has announced their intention to produce an expansion board that will boost its top frequency capability to 12 GHz, making it the only SDR of this bunch that could receive and transmit on both the 5.7 GHz C-Band and the 10.5 GHz X-Band. This is very exciting! Of course, it does not exist today, so we can't put all our eggs in that basket (yet).

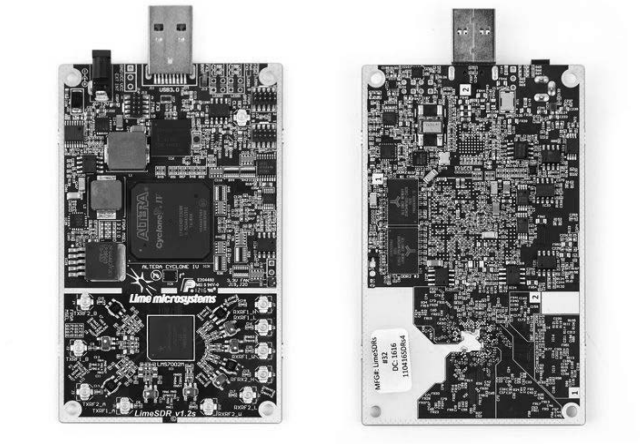
No existing SDR can do the whole job without some assistance. SDR's are designed to receive and transmit over a very wide frequency range, but their receive sensitivity is low, as is their ability to receive weak signals in the presence of other strong signals, and their maximum transmit power. Spurs can be a significant problem. Filtration and signal amplification will be needed. On the C-Band uplink, low-pass and/or bandpass filters plus a power amplifier will be needed for a clean, strong signal. On the X-Band downlink, high-pass and/or bandpass filtration plus a low-noise pre-amplifier will be needed to clearly receive weak signals. The uplink and downlink filtration is not only needed to prevent out-of-band transmission and to exclude environmental out-of-band signals that could overwhelm the receiver, but also to maximize the isolation of the 10.45 GHz receiver from the 5.6 GHz transmitter. This is especially an issue because of the nearly 2:1 ratio of the two frequencies. If the ground station needs only to *receive* X-band signals (*i.e.*, it will not be transmitting X-band signals for simplex communication with another ground station), it may be possible to use an inexpensive COTS satellite TV LNB in place of discrete filters and pre-amplification. On the other hand, for ground stations with the optional terrestrial X-band simplex operation mode, the inexpensive LNB can't be used; and in addition to filtration and a low-noise preamp, it will be necessary to add a power amplifier, additional output filtration, T/R (Transmit/Receive) switching, and in most or all cases, signal downconversion to a lower IF (Intermediate Frequency). A full transverter would perform all of these functions, particularly if the SDR is unable to reach X-band frequencies on its own, but it is *not* inexpensive.

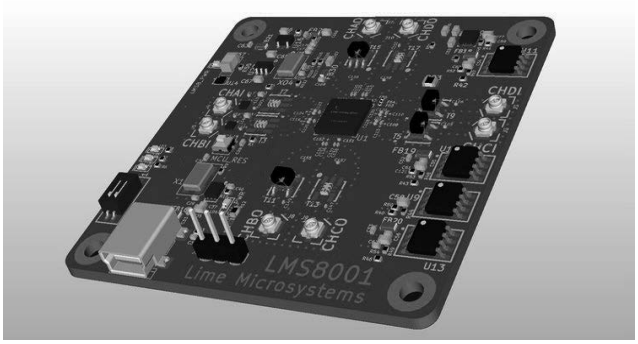
Computing hardware will be absolutely mandatory, to perform the software-defined RF signal modulation and de-modulation, the digital data encapsulation and extraction, and more. Nowadays, most Ham shacks have a laptop or desktop computer, and this may be adequate for the “budget” home fixed station. For portable stations in general, and EMCON stations in particular, a self-contained microcontroller or microcomputer will be highly desirable, to make the ground station self-contained, easy to deploy, and stingy with its battery power drain. At this point in time, the minimum computational ability of the external or embedded computer has not been determined. Will it need to be an Intel quad-Core i7 CPU, or will an ARM Cortex

processor be sufficient? Perhaps an ARM processor with additional GPU computational cores, like the nVidia Jetson TK1, which combines four powerful Cortex-A15 cores, one low-power core, and 192 CUDA GPU cores for parallel processing, will work. Testing continues.

In order to attract many Hams to operate on the P4 and/or P5 microwave satellites, the ground terminal needs to be affordable. There are a number of things that we are doing to keep the price down:

1. We are actively investigating the LimeSDR for its fine capabilities in its present form, and are especially hopeful that the LMS8001 expansion becomes available soon at an affordable price so that it can operate all the way up to 12 GHz without any other additional up-converter or down-converter.





2. We are evaluating the possibility of using a reasonably inexpensive FPGA (Field Programmable Gate Array) for the time-sensitive, computation-intensive functions that demand a high I/O transfer speed. The more of the digital signal processing that can be done in an FPGA, the less powerful (less expensive) the computer that is needed.

3. We are evaluating the possibility of using ASIC's (Application-Specific Integrated Circuits) to alleviate the computation burden and I/O transfer burden. A number of ASIC's exist for the DVB-S2x demodulation standard, since they are used in millions of satellite TV set-top boxes. Some of them claim to implement the VLSNR portions of the DVB-S2x standard, but to date, we have not found an ASIC that fully supports VLSNR properly, so we are still searching. Of course, satellite TV is currently one-way (*i.e.*, receive-only) for the consumer, so ASIC's to handle the DVB-S2x modulation standard for the ground station uplink are, not surprisingly, non-existent at this time. However, this is a rapidly-changing field, and we are keeping our eyes on the marketplace for new chips that may make the ground terminal simpler and cheaper. We are even investigating the possibility of using a COTS satellite TV tuner, which has DVB-S2x built in, to provide the demodulation of the P4/P5 downlinks, since some such tuners operate at frequencies immediately adjacent to the Amateur Satellite X-Band.

4. If you have been active on the 5760 MHz terrestrial weak-signal band, you know that linear power amplifiers for this band are expensive and low-powered. Ideally, we'd like our ground stations to be able to transmit with at least 5 to 10 watts of power to get a clean signal into the satellites. So the search is on for ways to generate more RF power on the 5 GHz C-Band. With the advent of Gallium Nitride technology, a number of power amplifier transistors for the 5 GHz band have finally become available, but the prices are quite high. Triquint offers a 1 watt part for over $40 each, making it quite expensive to reach the desired power level. They also offer a 40 watt part but it costs over $800 for the chip alone, not including all the support circuitry it would require. We have found an inexpensive C-Band power amplifier board (not just the chip) that has been measured to produce 3.5 watts before the onset of compression, and can be bought for only $30 - $40. Needless to say, this caught our interest. It uses two SkyWorks SE5004L 2.5 watt chips in parallel. It would be possible to plumb two of these boards in parallel, but an even better solution would be to design our own circuit board that parallels 4 of the SkyWorks chips with all splitting and combining circuitry on board, along with appropriate filtration to remove spurs and the first harmonic of the signal being transmitted. Once again, this is a work in progress.

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5. Already mentioned is the possibility of dealing with the very high downlink frequencies using SDR's that are unable to operate at X-Band frequencies on their own, by means of an inexpensive (~$30) COTS satellite television LNB (Low Noise Block down-converter). New PLL (Phase-Locked Loop) LNB models have sufficient stability for this application, and even though they are designed for the satellite TV frequencies above the Amateur Satellite sub-band, testing has shown them to be satisfactory all the way down to the bottom of the 10 GHz Amateur Radio sub-band, which is well below the bottom of the Amateur Satellite sub-band.

6. AMSAT is working with the GNU Radio community to accelerate the development and refinement of software for DVB-S2x encoding and decoding. Prior to AMSAT's selection of a modulation format for P4 and P5, there already existed GNU Radio software blocks for DVB-S and DVB-T which were provided by Ron Economos, W6RZ. At the request of AMSAT, Ron has also developed GNU Radio blocks for DBV-S2x. Seeing renewed activity in the GNU Radio community with respect to DVB-S2x is very encouraging, particularly because some portions of the standard in which we have a lot of interest (such as the VLSNR extensions) have not been widely implemented yet, so AMSAT may end up being on the leading edge (some would say, "the bleeding edge") of this technology's more widespread development and use.

Much of the complexity of the P4/P5 ground station is due to the software that still needs to be written:

1. Although there are a number of free, open-source software programs like PowerSDR, SDR#, etc. for performing the DSP functions that an SDR needs for modulation and demodulation of CW, SSB, and FM signals, there is precious little SDR software support for the DVB-S2x modulation schemes. Fortunately, AMSAT's activity in this regard has stimulated a re-awakening of interest in this area, so the situation there is rapidly changing. GNU Radio can do it today, but a dedicated program would be desirable.

2. The P4 satellite will be visible to nearly half of the planet at any time, and even though the transponder is expected to support more simultaneous QSO's than any prior Amateur satellite, there is a great deal of interest in preventing abuse of the transponder bandwidth by implementing a system of user identification, authentication, and confirmation of authorization. This will be especially important if the satellite is used during a crisis such as a severe weather disaster that brings down conventional communication channels. During such an emergency, we would want to reserve some or all of the transponder bandwidth for emergency traffic by authorized users, rather than allowing idle chatter or even signals originating with unlicensed persons. We currently envision using the ARRL's LOTW (Logbook of the World) database of subscribed users as a tool that can help us identify who is trying to use the (large, but still not unlimited) resources of the satellite transponder and decide whether or not to allow them to have access.

3. Work needs to be done on the channelization and sub-channelization process that will allow us to support an unprecedented number of simultaneous users.

4. Thinking outside of the box a bit, if the authentication of users is going to be assisted by accessing LOTW, it makes sense that QSO's can be automatically logged, since the system will "know" the callsigns of each of the persons involved in a QSO. Much of this software development is actually done already.

5. Although tracking P4 and P5 will be far easier than tracking the fast-moving LEO satellites, it would be very convenient if automatic satellite tracking was built into the P4/P5 ground stations. Automatic tracking, or at least performing the computations if not actually re-pointing the antenna(s), is a pre-requisite for automatic Doppler shift frequency correction. Since the X-band microwave downlink frequencies are 72 times as high as the frequencies in the 2 meter VHF band on older satellites, the Doppler shift is 72 times as large for any given range rate. Fortunately, these satellites will have very slow range rates, appearing to hover nearly motionless in the sky, which offsets the high Doppler shift that would otherwise be experienced. Nevertheless, for optimal digital signal integrity, keeping each user within their assigned channel or sub-channel will be much easier with automatic Doppler correction. Orbital prediction of P4 will be simple, using existing tools. Tracking P5 accurately will be a bit more of a challenge, since it will be using on-board thrusters to change its trajectory *en route* to Lunar Orbit, and because existing mathematical models of satellites in orbit around the Earth don't work for satellites in orbit around a satellite of the Earth (the Moon). However, simply pointing at the Moon (an easy computation) may be good enough, as was demonstrated by the Parkes Observatory Radiotelescope which had to quickly re-acquire a TV signal from Apollo 11 after a brief power outage reset all of their tracking computers.

The bottom line is,

If you are an RF Engineer or a Computer Software Engineer...

Volunteers are Still Wanted!

For more information:

https://github.com/phase4ground

https://phase4ground.slack.com

https://www.youtube.com/playlist?list=PLavdGnjBLuiX97DAKk32NJ1bCF1a0cv01

Using DVB-S2X and Annex M to implement low-cost Phase 4B Earth Station Terminals

Wallace Ritchie (WU1Y)

November 2016

Abstract

The AMSAT Phase 4 Ground Team has been evaluating DVB-S2, Generic Stream Encapsulation (GSE) and DVB-S2X extensions for use in the space to ground segment of the AMSAT Phase 4B Geosynchronous Satellite transponder. DVB-S2X provides extensions to an already complicated standard. However, use of the optional Annex M extension has the potential to actually simplify and reduce the computational complexity of Earth Terminals. This could potentially provide a significant reduction in the cost of low-end terminals in low manufacturing volumes with a resulting expansion of the population of Phase 4B users. This paper explores the DVB-S2X protocols and Annex M and how various features of these standards might be used to reduce the complexity of Phase 4B Earth Stations in the 10Mhz bandwidths anticipated for the Phase 4B downlink.

1 Introduction

The AMSAT Phase 4B project will place a Software Defined Digital Regenerative Transponder into Geosynchronous Earth Orbit (GEO) over North America. Unlike traditional bent-pipe transponders, which amplify and frequency convert signals from uplink to downlink, the P4B transponder is essentially a full duplex cross-band digital repeater. There is no analog signal path from uplink to downlink. Instead there is a multi-mode, multi-channel digital receiver bank and a single digital transmitter. A digital processing system forwards data from the multiple uplink receiver channels to the single channel downlink transmitter.

The specific functions performed by the P4B SDR Transponder will be determined by the Software and Field Programmable Gate Array programming uploaded from the ground. This allows these functions to evolve over time.

As currently planned, the satellite uplink will support more than 100 individual Frequency Division Multiplexed (FDM) carriers from individual ground stations with each carrier allocated within a 10MHz uplink bandwidth. The downlink will be a single modulated carrier occupying the allocated 10MHz downlink bandwidth. Digital data from the multiple uplinks will be received, demodulated, momentarily stored and then relayed over the downlink. This will provide digital simplex channels that can transport voice, messages, data, and IP traffic between earth stations in point to point or point to multipoint applications.

2 Digital Video Broadcasting

Digital Video Broadcasting (DVB) has been in use for nearly two decades to deliver Direct to Home broadcast television through GEO satellites. DVB is the most widely used digital transmission standard in the world. More than a billion DVB receivers are in use. Hundreds of millions of them support DVB-S/S2 based satellite transmissions.

The DVB-S family of standards has evolved over the years as digital television has advanced from so-called Standard Definition, through High Definition and now to Ultra High Definition TV (UHDTV). In addition, the standards have grown to support additional services enabled by the satellites e.g. IP downlinks, news gathering and professional applications.

In the typical DVB-S broadcast application a relatively high power earth station originates the modulated digital carrier and a linear or quasi-linear transponder in the satellite filters and amplifies the weak receive signal, frequency translates to the downlink band, and greatly amplifies the signal with a High Power Amplifier for re-transmission to the consumer ground stations. The basic configuration is one-way point to multipoint.

The Phase 4A Package built by AMSAT-DL will be onboard the Qatar Satellite Company's Es'Hail-2 satellite to be launched into a geostationary orbit. Currently planned for the 3rd quarter of 2017, this spacecraft is to provide coverage over Africa, most of Europe and Eurasia. The AMSAT Phase 4A package will operate much like the traditional DVB-S broadcast application over its 8 MHz linear transponder[1]. This transponder will be used to provide a very small number of digital carriers from select stations

[1] AMSAT P4A also carries a separate 250kHz linear transponder that supports narrowband analog signals.

including SDTV and HDTV transmissions. AMSAT P4A uses DVB-S/S2 more or less as intended – to deliver broadcast television. But P4A is also capable of transporting digital signals with suitable ground equipment (2.4 Meter Dishes, 100W 2.4 GHz amplifiers).

In contrast, AMSAT P4B uses the DVB-S2[1] formats for a different purpose - to multiplex all of the received uplinks into a single digital downlink carrier. Like AMSAT P4A, P4B can carry digital TV and Broadband Data. P4B, however, supports many narrowband *digital* uplinks using modest ground equipment.

The latest standards, DVB-S2, DVB-S2X[2], and the many optional features provided in their annexes provide an extensive menu of choices for P4B. While many of them looks inviting – one just can't just consume everything on the menu. Choices must be made and some of these choices are mutually exclusive.

3 Generic Stream Encapsulation (GSE)

Phase 4 Ground has been planning to utilize an optional DVB-S2 feature called Generic Stream Encapsulation (GSE)[3] to carry arbitrary Layer 2 MAC frames over the basic transport provided by DVB-S2 (or the even more flexible DVB-S2X). GSE provides a standard and efficient means to encapsulate IP packets for transport over DVB-S2 frames. Features include layer 2 header compression optimized for IP.

The robust Forward Error Correction (FEC) specified in DVB-S2 delivers the extremely low error rates required for the delivery of Digital Television streams and high latency IP packets. At present, the P4B downlink is exclusively IP.

3.1 DVB-S2 Physical Layer

The Physical Layer of DVB-S2(X) has a relatively simple structure. Symbols are packaged into slots of 90 symbols. Additional "Pilot Blocks" of 36 symbols are optionally inserted periodically into the frame. The pilot symbols aid the receivers in timing recovery and symbol alignment.

Every physical frame begins with a 90 symbol[2] PLHEADER that provides a start of frame (SOF) sync pattern of 26 symbols and a MODCOD that indicates the modulation and coding for the frame. The MODCOD is protected by its own heavy forward error correction to insure that it is correctly decoded even in the presence of errors. When the specified MODCOD indicates the inclusion of pilot symbols, then 36 symbols of pilot occur after every sequence of 16 slots (1440 symbols).

The physical layer carries PLFRAME DATA that consists of a fixed number of scrambled FECFRAME bits. FECFRAME bits are the bits that result after Forward Error Correction (FEC) coding has been performed on a chunk of data. The number of bits produced by the FEC encoder is either 16,200 or 64,800[3] coded bits. The number of original bits in the data depends on the modulation and coding selected for the frame and this can vary frame by frame. The MODCOD tells the receiver how many symbols of what modulation format to expect in the frame. For example, one of the heavily coded MODCOD indicates QPSK and ¼ RATE FEC with a Short FEC frame. With this MODCOD 3072 bits are input to the FEC encoder to produce 16200 coded bits which are then transmitted with 8100 symbols. This has an efficiency

[2] When Annex-M is used this is extended to 180 symbols.
[3] 32,400 is added as an additional choice in the DVB-S2X standard for certain coding rates.

of 0.38 symbols per bit. One of lightest coded MODCODs indicates 32APSK modulation with 9/10 FEC. With this MODCOD, 58,192 bits are input to the FEC block to produce 64,800 coded bits which are transmitted at 5 bits per symbol using 12,960 symbols. This has an efficient of 4.5 bits per symbol. This covers an almost 12 to 1 range and allow a corresponding wide range of signal to noise ratios to be accommodated by the system.

3.2 Baseband Frames (BBFRAMES)

BBFRAMES are the input to the FEC encoder. They have a length that is the same as the FECFRAME data. For each BBFRAME there is exactly one PLFRAME that will be transmitted. A BBFRAME includes an 80-bit Header that indicates what kind of data is in the frame. Since P4B downlink is planned to be all-IP, a BBFRAME will always contain only GSE packets.

3.3 GSE Packets

GSE Packets transfer the Protocol Data Units (PDU) from the Network layer. In P4B, a PDU is always an Ethernet Layer 2 packet, usually carrying an IP packet.

GSE packets cannot span multiple BBFRAMES, i.e. a BBFRAME must always begin with a GSE Packet header. However, the PDU that is being transported can be larger than a BBFRAME. Basically, GSE provides the means to transport PDU's by fragmenting them where necessary and packing them into GSE Frames that fit into BBFRAMES. The BBFRAMES are then FEC encoded and transmitted over the downlink as Physical Layer Frames.

The GSE Header provides all of the information necessary to reassemble the PDU's. It should be noted that GSE can handle fragmented reassembly for multiple interleaved PDU's. This allows the transmission of higher priority PDU's to essentially interrupt the transmission of lower priority PDU's. Whenever a high priority PDU is ready, the transport layer can begin sending its fragments at the next opportunity – even if the current PDU has fragments still remaining to be sent. Many different PDU's can be in process in various states of fragmentation. This feature allows an effective Quality of Service (QoS) capability to be implemented. Phase 4B will likely use this capability to transport isochronous streams carrying digitized voice channels.

3.4 Fragmentation CRC

When GSE Packets are fragmented, the final packet in the sequence contains a cyclic redundancy check (CRC). This is identical to the Ethernet CRC. The CRC assures that the fragmentation and re-assembly process occurred without errors. The entire PDU is dropped if the CRC is bad. The CRC is not used when the PDU is not fragmented, i.e. the PDU fits into a single GSE packet.

Note that if it can be assured that a PDU will always be fragmented, then the CRC will always be present. This fact can sometimes be exploited to skip FEC processing for a PLFRAME.

4 Very Low Signal to Noise Ratio (VL-SNR) MODCODs

The combinations of modulations and coding rates in the base DVB-S2 standard are well suited to the Direct to Home (DTH) television application. Other applications, however, may require the ability to work at even lower signal to noise ratios. DVB-S2X adds a new capability applicable to those applications.

To support these DVB-S2X VL-SNR MODCODs, a special 10 slot VL-SNR header is inserted after the normal PLHEADER. Since there are always 90 symbols in a slot, this additional header is 900 symbols long. Receivers that don't need to handle VL-SNR use the normal SOH and decode the MODCOD which gives them the length of the frame as well as the location of the pilot blocks. This allows them to remain locked during the VL-SNR frame. The VL-SNR stations use a correlator approach to synchronize and lock to the 900 symbol sequence in the VL-SNR header. This allows them to maintain synchronization lock with the downlink despite a very low signal to noise ratio. The codes also indicate the modulation, coding, and spreading that will be used for the symbols in the frame.

To maintain compatibility with normal receivers, the VL-SNR frame sizes are adjusted so that they remain compatible with the number of symbols used by the normal MODCODs.

5 Phase 4B Terminals

Several types of earth terminals are envisioned for Phase 4B. At the low-end is a single channel narrowband voice terminal providing reasonably good quality voice and/or low speed data. These terminals will operate with about 10 kHz of uplink bandwidth using small dishes. The design objective is to drive the cost of such terminals as low as possible.

At the mid-range is a multi-channel wideband terminal capable of carrying trunked narrow band channels and/or higher speed IP packet flows. The mid-range terminal is the so-called "Amateur Radio Access Point" that can aggregate traffic within a local area, e.g. from multiple VHF/UHF repeaters and/or point to point links to the public internet. These terminals will operate with uplink bandwidths on the order of 100kHz.

At the high end are terminals with up to 1MHz of uplink bandwidth. These will require higher power and larger apertures but will be capable of transmitting higher speed IP data streams, e.g. MP4 television.

6 Phase 4B Narrowband Services

Phase 4B will support voice services through the satellite for a large population of users. This is intended to provide point to point voice channels similar in function to SSB or FM voice channels used on the HF and VHF bands. In addition, P4B will support low speed data services equivalent to RTTY, PACTOR and PSK31. If a sufficiently low cost terminal can be created, these narrowband services will account for the vast majority of connections.

Since 4B will be in GEO, the mean half-hop delay through the satellite is about 260 milliseconds before accounting for processing delays within the satellite. This is already at the high range of acceptable delay for voice. Some additional delay must be added to accommodate jitter buffers when interworking with traditional voice paths e.g. VoIP.

Digitized Voice is essentially an isochronous application that requires a steady stream of packets with predictable delay and jitter characteristics. Packets that can't meet the schedule are generally dropped on the floor. Typical digital voice is compressed in 20ms frames resulting in 50 packets per second. Tolerance to packet loss varies with codec type but is typically in the 1% to 5% range.

Digital Voice has fundamentally different error performance requirements than digital TV or high latency IP traffic. The "cost" of an error in Digital TV or high latency IP is large. It destroys image quality or requires expensive re-transmission and delays for IP. This is why very strong error correction schemes are specified for DVB-S2. Voice, in contrast, involves very short packets (as low as 6 bytes per frame) and can tolerate losses of a few percent without major impact on perceived quality. Additionally, when multiple conversations are carried in a single packet, errors in the data that may affect one conversation may not affect others. This means that we potentially have the option of using a different approach to error correction for narrow band traffic. How this could work is discussed below.

7 FEC Coding

DVB-S2 uses a forward error correction scheme that performs close to the theoretical limit for the communication channel. This delivers the very low bit error rates that are essential for the high quality video that consumers demand. Achieving such high performance requires relatively large encoding blocks. DVB-S2 uses a concatenation of Low Density Parity Codes (LDPC) and BCH codes. These methods are computationally intense, especially for decoding. This doesn't matter much when Application Specific Integrated Circuits (ASIC) with volumes in tens of millions are involved. This is the normal case for Set Top boxes and other high-volume consumer products that are the targets for DVB-S2 receivers. It's a big problem, however, when using FPGA's that generally have costs proportional to resources.

The resource requirements for an FEC decoder also rise with the bit rate. While it is relatively easy for a receiver to synchronize to and demodulate high symbol rates, the FEC decoding process at such high rates requires lots of resources. These resources are wasted when the receiver only needs to decode a small portion of the bandwidth.

7.1 Systematic Codes

The BCH and LDPC codes used in DVB-S2 are so-called "systematic codes". This means that the raw data is present in the bit stream. Essentially, the FEC frame has a copy of the original data followed by a set of outer BCH code words that can be used to correct that data. This is followed by inner LDPC code words that can be used to correct the raw data together with their BCH codes.

When handling TV or TCP/IP streams the robust FEC is always required. A single bit error not corrected either destroys the compressed video quality or requires that the IP packet to be dropped. For isochronous digitized voice, however, we can tolerate a few bit errors or lost packets.

7.2 Ignoring and Enhancing FEC

Depending on the specific resources available in the terminal, we can 1) ignore the DVB-S2 FEC, 2) correct using just the outer BCH code, or 3) correct using the LDPC and BCH. In addition, we have the option of adding another level of FEC on the few bytes of data that matter for a single conversation. As the DVB-S2 FEC codes are systematic and the satellite channel is close to an AWGN channel, the error probabilities on individual bits are more or less independent. A relatively simple interleaved Golay code may be all that we need to recover our data to the extent required. For voice and text, we always have an additional final layer of forward error correction by that 100 giga-neuron neural-net processor between our ears.

Ignoring FEC does require that we use great care in how we construct the packets that carry narrowband voice data. Fortunately, this is straightforward. The narrowband digital voice and low rate data can be carried in GSE packets that contain an isochronous stream of UDP/IP packets that appear in a regular fashion in the stream. These carefully crafted UDP/IP packets can then be processed by receivers with or without DVB-S2 FEC.

8 Time Slicing

The previously described approach for narrowband services does not achieve everything needed for P4B. It works only for the narrow case of isochronous UDP/IP transport of digitized voice for which it is being proposed. We still need to use FEC protected streams to pass regular IP, particularly TCP connections.

In the commercial sector, the high data rates required for Ultra HD Television (UHDTV) are driving transponder bandwidths and symbol rates to higher and higher levels. These wideband transponders can have bandwidths from 72MHz to hundreds of megahertz. While demodulators can keep up with these high symbol rates, the task of FEC decoding in real time for an entire symbol stream requires computational resources significantly beyond those required for modulation alone.

Most applications do not need to decode the full bandwidth of the wide band carrier – just the streams for the services of interest. Requiring an FEC decoding capability for the full carrier bandwidth is uneconomic for many applications. The optional features of Annex M time-slicing are the Standard DVB-S2(X) solution to this need.

Annex M is designed to permit relatively low cost receivers to process a full wide band carrier (72 MHz – 300 MHz for example) without having to FEC decode all of the bits in the stream. Instead, a receiver demodulates the carrier but only FEC decodes the time-slots that it needs. While Annex M is designed for carriers on the order of hundreds of Mbps and timeslot streams on the order of tens of Mbps, it can also be used for the slower P4B application. In this case, Annex M could be used to reduce the workload of low cost terminals.

8.1 Modified PLHEADER

Annex M modifies and expands the normal single slot PLHEADER to two slots. This allows the header to carry an additional 16 bits that specify a time-slice. A particular PLFRAME belongs to a single time-slice and all of the time-slices in use are interleaved in whatever pattern is appropriate for the services offered. The MODCODs available are also expanded somewhat with additional choices made available as the result of the additional available bits.

With Annex M time slicing, a receiver essentially grabs the time slots that it needs while ignoring the rest. No FEC decoding is required for the frames of unneeded time slices. When the slices are adequately spaced, the bit rate required for the FEC decoder is well below that required for the entire stream. This lets a receiver operate with a 200Msym/s rate with an FEC decoder that provides only 20 Mbit FEC performance.

In the case of P4B, the symbol rate is already a relatively modest (for an ASIC or high-end FPGA) rate of 10Msym/s. However, a particular receiver may only need to process a more modest 1 Mega-symbols per second. This could be achieved with a much smaller FPGA and/or general purpose PC.

Unfortunately, Annex M must be applied to the entire carrier. It is a minor change to the header but all stations using the carrier must support it. Because of its advantages, it is likely that most future ASIC's will be supporting Annex M and will be able to sync on either Normal or Annex M carriers. Annex M is therefore a reasonable choice for P4B.

9 Summary

DVB-S2X and its Annex M provide a rich set of features that can be exploited in the design of Terminals, Satellites, and services for GEO satellites in the Amateur Radio Satellite Service. The amateur radio community has a long history of expropriating and repurposing technologies for different application and finding new ways of doing thing better and cheaper. The AMSAT ASCENT and Phase 4 Ground Teams are actively carrying on this tradition as Amateur Radio moves to GEO and beyond.

This paper has just touched on some ideas on the downlink. Many more innovations large and small are yet to come for downlinks, uplinks, the in-between, and the all around. These are exciting times for Amateur Radio.

[1] ETSI EN 302 30101: Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 1: DVB-S2

[2] ETSI EN 302 307-2: Digital Video Broadcasting (DVB); Second generation framing structure, chanItnel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications: Part 2: DVB-S2 Extensions (DVB-S2X).

[3] ETSI TS 102 606-1: Digital Video Broadcasting (DVB); Generic Stream Encapsulation (GSE); Part 1: Protocol.

AMSAT Goes to the Moon with the Cube Quest Challenge

Howie DeFelice AB2S

1. What is the Cube Quest Challenge ?

The Cube Quest Challenge was initiated by NASA's Centennial Challenge Program to award prizes to "citizen inventors" who can design, build, and operate CubeSats that successfully achieve lunar orbit – or else a range of 4M km – and then successfully demonstrate prescribed performance achievements of the kinds needed for future NASA missions. Though competitors may arrange their own launches in order to compete, qualified teams will be offered a free ride on the EM-1 mission. NASA's EM-1 mission, planned for launch in 2018, will be the first un-crewed lunar flyby of the Orion capsule mounted on the Space Launch System (SLS). NASA's Exploration Systems Directorate specified that the SLS would be designed to have capacity for 13, 6U-sized CubeSats, which could be loaded with any secondary payloads. The secondary payload dispensers are mounted inside a ring as part of the Interim Cryogenic Propulsion System (ICPS). The secondary payloads would be deployed after Orion separates and the ICPS performs a collision avoidance maneuver. The ICPS trajectory (and the non-propulsive trajectory of its deployed CubeSats) will be a lunar flyby trajectory that ultimately continues into heliocentric orbit. NASA's Space Technology Mission Directorate challenged its Centennial Challenges Program to determine a useful public prize that could make productive use of three of these available secondary payload slots.

The Cube Quest Challenge team consulted the CubeSat developer community, NASA stakeholders, other government agencies, and the STMD sponsors while crafting the rules of the competition during a period lasting from the fall of 2013 until fall of 2014. Two drafts of the Cube Quest Challenge rules and proposed prize structure were released to Federal Business Opportunities for RFI. Relevant comments from the CubeSat developer community were incorporated into re-drafts of the rules. There are a number of considerations in the selection of the final challenge scenario:

A. Deep Space Derby

The demonstration of advanced capabilities for high-speed, very long-range communications from a CubeSat to an Earth ground station, over a sustained period of time, will be a huge milestone for CubeSats designed to operate in deep space. For the so-called Deep Space Derby, prizes would be offered for achieving a minimum data rate, minimum data volume over a specified time interval, closing a communications link for distance at least 4M km, and for spacecraft longevity at this range, as demonstrated by counting the elapsed number of days between the first and the final successful spacecraft communication dates. The 4M km range is almost 10 times the distance from earth to the moon. To be eligible for prizes, NASA would independently verify the range and the communication achievements.

The above description of the Deep Space Derby and the prizes awarded center on communications accomplishments. That is because radio (or optical) transmissions are straightforward ways to demonstrate satellite activity. It should be realized, however, that achieving high data rate communications from a very long range, and surviving to communicate after many days or weeks, necessitates the CubeSat designer to stretch the entire system of CubeSat capabilities. Example: To communicate long distances requires precision navigation and attitude determination, to aim a high-gain antenna to Earth. To date, no CubeSat has navigated without aid of GPS or Earth's magnetic field. These are unavailable to our Deep Space Derby challengers.

Cube Quest teams may employ NASA's DSN high-gain antennas for their ground station needs, however they must do so at their own cost and they must vie with all the other EM-1 payloads and NASA mission to schedule aperture time. Some of the Cube Quest teams indicate they intend to use alternative ground stations or to design their own. Exercising the capabilities of these non-NASA ground station resources will pave the way for other inexpensive private missions to come.

High RF communication rates implies high-powered transmitters, requiring advanced power generation and power management tactics, especially challenging when solar array sizes are limited by the small 6U CubeSat volume.

To communicate over a range of many weeks, the CubeSat will have to be designed to tolerate the high radiation environment of deep space. Exposure times and dosages are much greater here than they are around low Earth orbit.

Likewise affecting longevity, the ambient thermal environment of deep space is different than for CubeSats in LEO. Traveling away into heliocentric orbit, CubeSat's will not have the thermal radiation from Earth's albedo, yet still have to cope with the internal heat dissipated by large radio transmitters enclosed in the small 6U volume. As stated above, the Cube Quest contestants who develop these advanced CubeSat capabilities will be creating the technologies needed for future NASA and other exploration and science missions. One simplifying factor of the Deep Space Derby is that, at least for those deployed from SLS, the CubeSats will not need to include any propulsion system (other than that needed for attitude control). The SLS will deploy its EM-1 payloads into a hyperbolic lunar flyby trajectory, so that they will be at a range of 4M km within a few days afterdeployment, even without propulsion. This simplification leaves designers with more volume, mass, and power for their transmitters and other electronics.

B. Lunar Derby

Similar to the Deep Space Derby, contestants in the Lunar Derby will demonstrate high-speed data communications and long-term viability, but only after they have first achieved a lunar orbit (as specified and verified by NASA). Again, prizes would be offered for achieving a minimum data rate, minimum data volume over a specified time interval, and for spacecraft longevity while in lunar orbit, as demonstrated by counting the elapsed number of days between the first and the final successful spacecraft communication dates. Another prize would be given to operators that successfully inert

their CubeSat into an orbit specified by NASA. As in the Deep Space Derby, NASA would independently verify the lunar orbital trajectory and the communications achievements. Achievements of the communications goals would require designers to deliver a CubeSat with all the system capabilities listed in the Deep Space Derby objectives, plus, the developers have to include a propulsion system and operators must navigate their spacecraft into lunar orbit after being deployed by the SLS or their third-party launch vehicle. Based on preliminary trajectory and deployment concepts for EM-1, the CubeSats are estimated to need to achieve about 700 to 900 m/s delta-V to be inserted into a stable orbit. What's more, they will need continuous navigation –either autonomously or via Earth-based command and control – to station-keep that orbit while attempting the communications achievements. The satellite power management systems will also have to cope with Earth and lunar eclipses while generating and storing solar electric power.

The ASCENT team reports to AMSAT's VP of Engineering and is funded as deemed necessary by the AMSAT Board of Directors.

2. What is AMSAT's role in the Cube Quest Challenge?

AMSAT is providing the communications capabilities to Ragnorak to:

- Provide command and control between the spacecraft and ground
- Provide ranging data for orbit determination to approx 15M accuracy
- Provide high speed data for Lunar Derby competition
- Provide amateur radio transponder for post mission usage

AMSAT will promote participation in the reception and reporting of ranging measurements and Lunar Derby data. The design of the communications package will serve as a model for future high altitude cubesat payloads. The ASCENT team is leading this effort within AMSAT.

3. Ragnarok Heimdallr satellite overview:

The Ragnarok 6U cubesat will be inserted on a lunar trajectory by the NASA SLS vehicle. The spacecraft controllers will use a low energy, long duration, electronic thruster to gradually ease the satellite into lunar orbit. It will take 3 to 4 months to achieve gravitational capture by the moon and another 3 months to spiral down to the desired orbital height. The satellite will use 3 axis stabilization with rate gyros for attitude control. A star tracker and sun sensor will aid in attitude determination. To generate the large amount of power required for the hall effect electronic thruster, a steerable solar array capable of generating up to 100 Watts of power will be supplied. The communications equipment will use both directional patch arrays and omni-directional antennas.

4. How is this important to amateur radio ?

In an era where everyone is continuously, wirelessly connected across the world, the traditional value of amateur radio as a medium for remote communications is not as compelling as it once was. The challenges of a lunar mission provide many exciting areas of development of interest to the current generation experimenters. Flying a satellite a million kilometers away using a digital communications link you helped design is way better than flying a quad copter in the back yard. AMSAT also has an opportunity to show its value to the scientific community. This will be the only mission in the Cube Quest Challenge that will use a volunteer network of amateur radio operators to provide the tracking and orbital determination data for a lunar mission. For AMSAT, this marks the return to high earth orbit.

5. What will the comms payload provide ?

As mentioned earlier, the communications payload will provide the necessary telemetry, tracking and control functions required to fly and operate the satellite. The primary mission will end in approximately one year. At that time the satellite will be turned over to AMSAT to operate as a communications satellite. The downlink will be in the 10.5 GHz. band and the uplink will be in the 5.6 GHz. band. The primary mode will be a digital regenerative transponder. The digital transponder will have four 5 Kbps digital voice uplinks. Each of these uplinks will be regenerated on the satellite and multiplexed onto a single 25 Kbps downlink. By regenerating the signal on the satellite, all the noise added on the uplink is removed before being re-transmitted to the ground. The satellite will also have a linear transponder in the same band as the digital transponder. The primary purpose of the linear transponder is to allow the ranging function to be carried out in case of a failure of the SDR radio used in the digital transponder. Since it will be on the satellite we can make it available for those with EME class stations on a scheduled basis.

6. What will I need to hear the satellite and communicate through it ?

The AMSAT ground terminal being developed for P4 will also work with this satellite. The proposed 1M antenna on the ground terminal will work for receiving telemetry and making ranging measurements. To communicate using the digital transponder the antenna will need to be upgraded to about 1.8M using the current link budget. Work is underway to try to squeeze a little more gain from the spacecraft antenna in order to reduce the ground side antenna. There is plenty of room for homebrewing and innovation as well. Low cost TVRO LNB's are available on eBay and a low cost RTL-SDR should be capable of receiving the downlink with the appropriate software. The uplink is a little more difficult but may be possible using transverters with a radio capable of generating the 5 Kbps BPSK uplink. New SDR platforms are becoming available at reasonable prices that will be able to transmit at 5.6 GHz directly without the need of a transverter. The uplink will require about 48 dBW of EIRP or 10 watts into a 1.8M antenna.

7. Help Wanted !

There is allot of work left to do and the ASCENT team can use all types of talent. In particular we need volunteers with time and:

- SDR programming experience
- FPGA experience
- Micro-controller programming experience
- Schematic capture and R.F. PCB layout experience
- Documentation and project management experience

Please volunteer online at the AMSAT website.

ASCENT

AMSAT's Skunkworks

Bill Tynan, W3XO

How it Began

Several years ago, a group of AMSAT volunteers, including Jan king, W3GEY, Dan Schultz, N8FGV, Phil Karn, KA9Q, Nick Pugh, K5QXJ and the writer, proposed to the AMSAT Board of Directors a design for a 6U CubeSat to go into a Geostationary Transfer Orbit (GTO). This was to be submitted to NASA in connection with its ELaNa program, the same NASA program that resulted in a free launch for Fox-1, now AO-85. Unfortunately, the Board felt that the proposal was not complete enough, and there was only one month before that year's ELaNa proposals were due.

Nevertheless, this activity brought to light the need for a group of AMSAT volunteers to focus on development of new technology for future launch opportunities. Tom Clark, K3IO, dubbed this AMSAT's Skunkworks. AMSAT's VP Engineering, Jerry Buxton, N0JY, jumped on the idea and termed it ASCENT for Advanced Satellite Communications and Exploration of New Technology.

Thus ASCENT was officially born as an AMSAT activity.

In all previous AMSAT activities, involving exciting and challenging projects, volunteers rushed to participate – many not previously involved in AMSAT endeavors. This has also proven true in the case of ASCENT.

ASCENT's Current Activity

About the time Fox -1 (AO-85) was being completed, three new exciting potential launch opportunities presented themselves. One of these, termed P3E, involved employing a spaceframe built in Germany but never launched. It was to be shipped to the U.S. and outfitted with a new Amateur Radio electronics package plus a U.S. government experiment. The resulting spacecraft was to be launched into a Molniya style orbit by the U.S. government. Unfortunately, this opportunity, dependent on the U.S. government mission, did not come to fruition.

However, two other projects, ARE proceeding. One of these being called Phase- 4B (P-4B). The other is Phase- 5 (P-5). P 4B refers an amateur radio package to be placed aboard a large geosynchronous satellite being built for the U.S. government by Millennium Space Systems of El Segundo, California (Figure 1). AMSAT has already funded a compatibility study resulting in production of an Interface Control Document defining the physical space, electric power and other details associated with inclusion of the amateur radio package on the satellite.

P-5 refers 6U CubeSats entered in NASA's CubeSat Quest Challenge (CQC) competition. Since this spacecraft is to leave Earth orbit, the designation, Phase 5 seems appropriate as all former amateur radio satellites that AMSAT has been involved with, (Phase 1, Phase 2 and Phase 3) were and are in Earth orbit. This competition involves accomplishing one of two objectives. One is for a 6U CubeSat to orbit the Moon. The other is to transmit data back to Earth from a distance of at least four million

kilometers. NASA will launch the winning contestants into a translunar trajectory, but the rest is up to the organizations building the winning CubeSats. The competition is open to both commercial and non-profit organizations and includes a number of reviews by NASA officials. Winners will be selected based on these reviews. AMSAT has partnered with a start-up called Ragnarok Industries Inc. that is handling the satellite design, construction and testing while AMSAT/ASCENT, under Howie De Felice, AB2S, is responsible for providing the spacecraft radio and related equipment.

The P-4B amateur transponder to be installed on the Millennium Space Systems satellite is the is the responsibility of Virginia Tech. under Bob McGwier, N4HY, and his associates and students, but the design of the special ground terminal equipment needed to access this satellite is up to AMSAT. Meeting this challenge is the task of volunteers that have formed, what they call "Phase 4 Ground." This group is comprised of some of the people involved in an earlier endeavor to produce equipment in connection with a possible rideshare opportunity on a commercial geostationary satellite that AMSAT was not able to take advantage of. Michelle Thompson, W5NYV, chaired the Microwave Experimental Project, MEP that was active in that earlier effort and is leading the current Phase 4 Ground group. Much of the work on ground station equipment being developed for P-4B by Phase 4 Ground will also be applicable to P-5 but higher transmit power and significantly larger dish antennas will be necessary to communicate with the spacecraft at the much greater distances.

Figure 1: The Millennium Space Systems Aquila M8 Bus, the host for Phase 4B amateur transponder, with (L to R): Virginia Tech Hume Center Project Manager, Sonya Rowe, KK4NLO; AMSAT Vice President Engineering, Jerry Buxton, N0JY; Hume Center Director of Research, Bob McGwier, N4HY; Qualcomm Co-founder, Franklin Antonio, N6NKF; AMSAT Board Member and President Emeritus, Tom Clark, K3IO; and Qualcomm retirees Michelle Thompson, W5NYV, and Phil Karn, KA9Q.

Why is it called Phase 4B, not Phase 4A, you might ask? Phase 4A is the designation given to the AMSAT-DL package destined to fly on the Qatar Satellite Company's Es'Hail-2 satellite to be launched into a geostationary orbit in the 3rd quarter of 2017 providing coverage of Africa, most of Europe and much of Eurasia.

Why is special ground station equipment needed? Can't amateurs employ the gear they already have acquired for use on other amateur satellites?

The answer is NO, they can't.

Other than the Millennium Space System Aquila M8, most of the spacecraft we will be dealing with now, and in the future, will be much smaller than the suitcase, or hot tub (AO-40 is about the size of a hot tub.), size satellites AMSAT has been involved with in the past. Thus, antennas will have to be much smaller. It's hard to envision an effective 2 meter, or even 70 cm antenna, on a shoebox size 6U CubeSat. To achieve the small antennas that can be accommodated on CubeSats, we must go up in frequency – way up. Another reason to go up in frequency is to provide wider bandwidth than heretofore. This will allow greater multi-channel capability, significantly increasing the number of simultaneous users that can be accommodated - well beyond the capacity of any previous amateur satellite. Greater channel capacity will also permit the transmission of high speed data, including television.

While the Millennium Space Systems satellite looks as if it could accommodate almost any antennas we can think of, the amount of antenna space available to the amateur package will be limited. Antennas required by the paying customer, in this case the U.S. government, must have first call on Earth facing satellite real estate.

During the formulation of the CubeSat to GTO proposal, mentioned above, Jan King pointed out that if one assumes a particular physical size for an antenna, its effectiveness (transmitted ERP, and receive capability) is proportional to the SQUARE of the frequency.

Thus if we must be dealing with small antennas, this is another reason we must go up in frequency.

Therefore, it has been decided that the new generation of AMSAT uplinks/downlinks will be 5 GHz up and 10 GHz down, AND digital. AMSAT refers to this 5 GHz up and 10 GHz down as our "five and dime" approach.

Why digital?

Digital transmission offers a number of advantages over analog *e.g.,* FM, single sideband voice, or CW.

1. The signal can be made noise free.
2. Error correction schemes can be used to provide perfect, or near perfect, copy.
3. It offers greater flexibility in the kind of transmission accommodated, i.e. voice, data or video.

Where do I get digital gear for 5 and 10 GHz?

Few hams are equipped for digital transmission and reception at 5 and 10 GHz. That's where Phase 4 Ground comes in. This group is developing complete suites of equipment to enable amateurs to take advantage of the aforementioned satellites as well as future ones that might come along.

It is envisioned that P-4B ground station equipment will come in several configurations. For what is termed the "bare bones" station, a cost objective in the order of $1,000 has been set. A price tag much higher this, it is felt, will deter many amateurs from taking advantage of the potentials offered by P-4B, P-5 and future satellites.

Another configuration, called ARAP (Amateur Radio Access Point), is also being pursued. This is a portable station that can sent anywhere in P-4B's footprint in times of emergency to provide terrestrial repeater access to the satellite. Thus hams helping in the emergency will be able to communicate, through the repeater and the satellite, with whatever authority they need to - regardless of its distance from the location of the emergency. It is evident that such a package will cost well in excess of $1,000.

This paper will consider only the "bare bones" station suitable for the average ham who wants to take advantage of the tremendous potential that the amateur transponder aboard Millennium Systems geosynchronous satellite will offer as well as perhaps participate in the P-5 mission.

Why don't you put up a stationary satellite?

That's a question that hams have been asking almost since the founding of AMSAT back in 1969.

The answers to this are many, but, principally cost and complexity are the major impediments to a small volunteer organization constructing, launching and maintaining a geostationary satellite.

Nevertheless, about 1990, AMSAT, under its then Vice President for Engineering, Jan King, AMSAT did pursue a project for a geostationary satellite. Figure 2 shows the concept of what was being studied at that time.

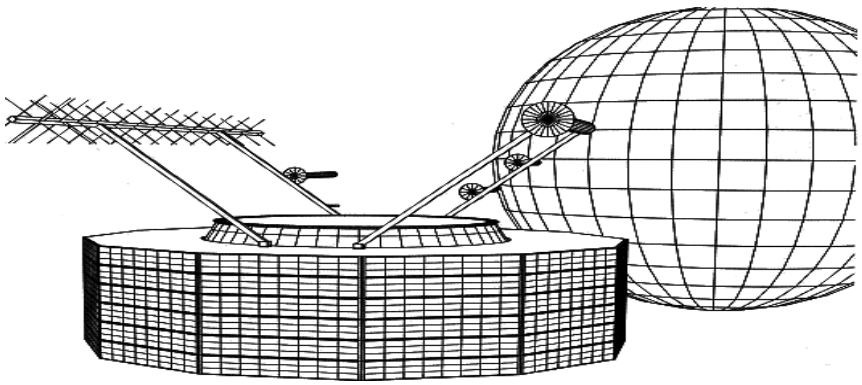

Figure 2 AMSAT's Geostationary Satellite Proposal, circa 1990

This project was shelved for various reasons. One was that all of the tremendous amount of money necessary for such a project, had to be raised only from the portion of the world that would be in its footprint, in this case, North and South America. The other was because the AMSAT-NA Board of Directors had agreed to participate, with AMSAT-DL and other overseas groups, in the Phase 3D project that culminated in the launch of AO-40 in November, 2000. It was obvious to the board members that two such huge projects could not be undertaken at the same time.

But, now with P-4B, the dream may finally become a reality.

The P-4B/P-5 "Bare Bones" Station

As stated previously, we must go way up in frequency and to accommodate a greater number of users, we must provide for higher bandwidth as well as digital transmission and reception. Thus, the amateur transponder aboard the Millennium Space Systems Aquila M8 spacecraft will transmit a 10 MHz wide stream of data between 10.450 and 10.500 GHz and receive a 10 MHz wide slice of spectrum between 5.650 and 5.670 GHz. The uplink will employ FDMA (Frequency Division Multiple Access). That merely means that each station uplinking, will be on a separate 100 kHz wide channel. This provides for 100 simultaneous voice or moderate speed data users with lots of room for applying techniques such as FEC (Forward Error Correction) to maximize error-free transmission. Use of the Free DV Codec, developed for amateurs by David Rowe, VK5DGR, is proposed for voice transmission.

Unlike the uplink, the downlink will be a 10 MHz wide stream of data with all of the uplink signals streaming on one carrier. The ground station's job then, is to separate this streaming data into discrete signals and select the desired one. It has been suggested that one way of accomplishing this is to employ a scheme used for satellite TV reception, called DVB-Sx (Digital Video Broadcasting Satellite, version 2, eXtended), that provides very low signal to noise (SNR) performance. And, since the hardware and software designs for this are already done, this should shorten the design timespan for coming up with a design for a P- 4B/P-5 ground terminal. The use of DVB technology is covered in greater detail in two other papers being present at the Space Symposium one by Wallace Richie, WU1Y, and the other by John Toscano, W0JT.

SDRs to be used

SDR, Software Defined Radios offer much greater flexibility than do conventional approaches using discrete transistors, capacitors, inductors etc. Therefore, the space equipment for P- 4B and P-5 spacecraft will employ software defined transponders. Accordingly, it is appropriate that the ground terminal do likewise. A number of different SDRs have been looked at for this application. John Toscano, W0JT, in his Space Symposium paper, treats the various potential SDRs, along with other aspects of the P-4B ground station design in greater detail.

None of the SDRs that W0JT will discuss are currently capable of operation at 10 GHZ, so a downconverter will have to be used to bring the 10 GHZ signal from the satellites down to a frequency within the SDR's range. However, some of them do cover up to 6 GHz, so, presumably they could be used for the uplink, in conjunction with a suitable RF power amplifier.

What to do about antenna(s), power amplifier for the uplink, and a low noise amplifier for the downlink. How costly will they be?

In the case of the P-4 "bare bones" station, the concept is to use two dishes, each about 1 meter (roughly 3 feet) in diameter - one for transmitting the uplink signal and the other for receiving the very feeble downlink signal. For the P-4B uplink, a power level of about 5 to 10 Watts has been deemed adequate. However, more power and larger antennas will be required to communicate with P-5. For the downlink, a low noise amplifier (LNA) will be required for both P-4B and P-5. These items sound costly. So how can the goal of about $1,000 for the complete ground station be met?

For the downlink low noise amplifier, it has been found that many satellite TV LNBs, though designed to operate at 12 GHz, work well down below 10.5 GHz. Many of them cost about $30, making them a great choice. And they downconvert to around 1 GHZ, where any of the SDRs W0 JT will discuss will certainly work fine.

The uplink power amplifier can be one of the high cost items. But one approach to getting the price down is to employ one or two of the power amplifiers built for controlling drones. These 3 Watt units sell for about $35. Two can be used with a combiner to deliver about 6 Watts, close to the 10 Watts estimated to be needed. Or, a single one could be used with a somewhat larger dish. W0JT discusses the use of these devices in his paper. In addition, appropriate surplus units have been purchased for about $30. There may be more out there.

But, We're not done

It is obvious that an SDR must be used with a computer. Most amateurs already possess computers, capable of handling the computation load needed to run an SDR. Interfacing the SDR to the computer is one of the issues being worked vigorously by the Phase 4B Ground team. It has been suggested that an FPGA (Field Programmable Gate Array) and appropriate software will be necessary to accomplish this, although others have claimed that a USB-3 interface will be sufficient. Another possibility might be to use a Firewire or Ethernet connection. Flex Radio uses Firewire for its Flex 3000 and 5000 radios and Ethernet for the new 6000 series. This subject is also covered in more detail in W0JT's presentation.

Help Wanted

This paper is intended only to outline what is needed, to come up with a design for a P-4B/P-5 "bare bones" ground station, not to design the system. It is obvious that a lot of detailed work is yet to be done. If you believe that you have appropriate hardware and/or software skills to contribute, and would like to take part, please express your interest to AMSAT's Vice President Engineering, Jerry Buxton, N0JY, via the AMSAT Website.

This is exciting stuff and I am sure that there are many of you out there who would love to participate.

Finding Veronica:
Methods for Obtaining Recordings of Satellite Passes
and
Searching for Fox-1 Satellite Telemetry Beacons
using Known Noise on an FM demodulated downlink

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Two methods for obtaining recordings of satellite passes and a new approach for finding Fox-1a (and other) satellite telemetry beacon signals on an FM downlink using non-telemetry known reference signals

Fox-1a sends down telemetry in three different ways: data-under-voice telemetry sent simultaneously with the user transponder audio, data-under-voice telemetry sent with a regularly scheduled voice ID beacon after a two minute period of inactivity and data-under-voice telemetry sent with a safe mode ID voice beacon. The voice IDs are prerecorded audio where Veronica[6] announces “Hi, this is amateur radio satellite Fox-1” or “Fox 1 safe mode.”

In all three modes the FM downlink contains a data-under-voice telemetry sent simultaneously with the transponder audio but the telemetry is lower in frequency than the transponder voice audio. In the first mode the downlink is FM modulated and the users sending their voices through the transponder are effectively an “unknown spreading” of the FM signal’s frequency when viewed at RF. We don’t know what they’re saying, so we can’t know how to digitally remove their voice from the FM signal at RF. If we FM demodulate the signal, then we can separate the audio with the voices and the audio with data.

In the other two modes, the beacons actually contain a short burst of unmodulated carrier just before the data. Due to the electronics, the carrier is not at a steady frequency but “swishes” several kilohertz. This is called the “fox tail” due to its appearance on a waterfall display and its resemblance to the curved tail of an actual fox. This is a unique and detectable signal on an SSB or SDR receiver. However, if a particular ground station is using an FM receiver then that unmodulated swishing carrier is (probably) not as noticeable or detectable as the longer voice ID transmission containing Veronica’s voice. If the ground station only has FM reception, then the combined telemetry and voice ID audio will be the only audio for a telemetry program to process. Detecting and identifying the unmodulated swishing carrier on an FM receiver, perhaps by detecting the relative silence and looking at the slope of the changing voltage output from the FM discriminator, is left as an exercise to the reader. Measuring the frequency of the “fox tail” carrier, calculating Doppler, TCA, and eventually TLEs is a separate project by the author.

One man's trash is another man's treasure

Much like the truth, whether something is signal or noise depends greatly on your point of view.[2] If you only want to use the FM voice transponder, then the telemetry beacon's signal (the subaudible "data under voice" data below about 300 Hertz) is noise to you. It would normally be filtered out by the audio filters in the FM receiver, so you probably will not hear it much, if at all. However, if you only wanted to receive the telemetry beacon, then the voices heard above 300 Hertz are the noise that has to be filtered away.

After FM demodulation, the user voices are above 300 Hertz and the telemetry is below 300 Hertz. If the signal is weak the forward error correction (FEC) will help, but can we help it further, particularly for telemetry sent after inactivity or in safe mode. One of the problems is determining when a telemetry frame starts. The Fox-1 telemetry downlink doesn't contain a SYNC vector to help identify the presence of telemetry signals, and the start of frame byte is only eight bits, so it is easy for it to be corrupted by noise or for noise to impersonate the expected eight bits.

Success is sometimes defined as turning a disadvantage into an advantage. We don't know what the users are saying, so their added energy to the downlink signal is a disadvantage. If only we knew what they were going to say, before they say it, then we could digitally subtract it out as we hear it. If we knew what they were going to say, we could even use that known audio to search for the satellite signal, which might be useful if the satellite is running with a low power output in safe mode and we're searching blindly for its signal.

We do know what the audio will be when the audio is a recording of Veronica. When the satellite is in beacon mode or in safe mode you can hear the prerecorded audio from Veronica, the voice of Fox-1, saying "Hi, this is amateur radio satellite Fox-1" or "Fox-1 safe mode." We have the original recordings for both as "Veronica Fox-1.wav" (4.1 seconds) and "Veronica Safe Mode.wav" (about 2 seconds). Instead of looking for a SYNC vector, which we don't have, or looking for the start of telemetry byte, we could look for Veronica. The author is working on a method using correlation with FFTW and libxcorr or another correlation package to identify Veronica in the downlink recordings. Her voice begins at the start of the second telemetry frame, so finding the start of Veronica's audio finds the second telemetry frame and since the size of the frame and the bit rate is known we can calculate backwards to find the exact start of the first frame. Veronica is or will be present on all of the Fox satellites, so this method will not be limited just to Fox-1.[6]

Telemetry Beacon, Telemetry Beacon, where for art thou Telemetry Beacon? [4]

While the telemetry reception is excellent over the US, Europe, and some other places, there are still large gaps over sections of the planet. If we only had more ground stations that could receive the signal, we could cover the gaps. There are several ways to get the data, but in simplest terms you can either do it yourself or get other people to do it for you[7]. The former has the problem of poor spatial diversity

whereas the latter has some limitation on how much data you can pull across the network. IQ recordings can get quite large.

Photo 1 – from http://www.websdr.org showing SDR stations that can receive at least some of the two meter band. Map by Google maps.

One method to get recordings is to use the WebSDR network of receivers at www.websdr.org. This page lists a collection of currently active SDR receivers that can be connected to over the Internet with options to filter by band and region. For Fox-1, filter by “2m” for the two meter downlink. This displays a list of receivers that can receive two meters (although some receivers can receive on two meters but cannot receive the frequency of the Fox-1 downlink). The station listing also includes the Maidenhead grid square where the receiver is located, so it’s possible to compute satellite passes for Fox-1 for this receiver. A map also shows the locations of the stations.

Now we know of the existence of multiple ground stations, and potentially multiple satellites to track. This brings up the next problem: which satellite will appear next over which ground station? Assuming we know the Maidenhead grid squares of the receivers, the TLEs for the satellites and that we have Linux, bash, and predict, then we can write a simple script to compute all of the next passes at each location and find out which one is next. For each ground station, create a qth file for predict with the name, latitude, longitude and elevation in the file. Run predict using that station’s location to obtain that station’s next pass information, saving it to a unique file.

```
echo 'Calculating passes for 2m satellites'
groundstations=(IO91of GG56tv ka2upw KG43ar JN78sk)
satellites=(AO-85 UKUBE-1 UO-11 ISS DO-64 AO-73)
for gs in "${groundstations[@]}"
do
   for sat in "${satellites[@]}"
   do
     echo -n $gs $sat...
     predict -t amsat.tle -q $gs.qth -p $sat -o next-$gs-$sat
```

```
      echo -n ...
      ./summarize-satellite-pass.sh  next-$gs-$sat $gs $sat >> summary
      rm next-$gs-$sat
      echo Done.
   done
done
```

Then combine all of the lines output from predict for that location to determine the start, end, and maximum elevation for that pass.

```
AOSunixtime=0
AOSdate=''
AOStime=''
LOSunixtime=0
LOSdate=''
LOStime=''
maxel=-1

while read p; do
  currentunixtime=`echo "$p" | cut -d' ' -f1`
  currentdate=`echo "$p" | cut -d' ' -f3`
  currenttime=`echo "$p" | cut -d' ' -f4`
  currentelevation=`echo "$p" |  tr -s ' ' | cut -d' ' -f5`

  if [ "$AOSunixtime" -eq 0 ]; then
     AOSunixtime=$currentunixtime
     AOSdate=$currentdate
     AOStime=$currenttime
     LOSunixtime=$currentunixtime
     LOSdate=$currentdate
     LOStime=$currenttime
     maxel=$currentelevation
  fi
  if [ "$LOSunixtime" -lt "$currentunixtime" ]; then
     LOSunixtime=$currentunixtime
     LOSdate=$currentdate
     LOStime=$currenttime
  fi
  if [ "$maxel" -lt "$currentelevation" ]; then
     maxel=$currentelevation
  fi

done <$1
echo $AOSunixtime $LOSunixtime $AOSdate $AOStime $LOSdate \
   $LOStime $maxel $2 $3 $4 $5 $6 $7
```

The only problem left is to connect (manually) to the appropriate websdr station at that right time, set the receive frequency (exactly) and start recording the FM audio. The author is currently trying to find a

way to either automate the WebSDR recording programmatically or get the recordings some other way. Obtaining raw I and Q instead of FM demodulated audio is another unrealized goal. As a proof of concept, the author was able to record audio from a websdr station in KG43 and later extract the telemetry using FoxTelem and upload it to the Fox-1A telemetry leaderboard.

Doing it all yourself - Raspberry Pi and RTLSDR on websdr

On the other hand, you can make the recordings yourself using just a Raspberry Pi running Linux and an inexpensive RTLSDR dongle. There's a simple script called "sdrrecorder.sh" [8] that will record at a predetermined time and frequency. I started with this script and made a number of modifications.

If you set the center frequency of an RTLSDR dongle near 145.180 MHz then the bandwidth of the receiver will extend from about 144.180 MHz to about 146.180 MHz. This fully covers the 145 MHz satellite subband from 145.8-146.0 MHz but it also extends low enough to include the APRS network at 144.390 MHz and leaves enough room at the edges so that SDR programs like SDRSharp can still process the signals in the recording. The presence of any APRS signals at the lower end in the IQ recordings will assure you that you recorded the correct range of frequencies and that the receiver, preamp, and the antenna are working as expected[5]. This is particularly useful information if you didn't find any satellite signals in the recording.

Under Linux, we use the rtl_sdr program to record the samples, but there are a couple of limitations to overcome. If we want to record at 2,048,000 I/Q samples per second then we will be creating some rather large recordings. Usually we would use the "-n" parameter to tell rtl_sdr when to stop, but the parameter for "-n" is only a uint32 representation. The longer satellite pass recordings will quickly get more samples than the biggest sample number we can pass in for "-n." If you leave off the "-n" parameter when starting rtl_sdr, then the recording will keep running, and it won't ever stop. We still want to stop the recording after the pass is over, so we can create a pipe and use the Linux/bash "head" program to end the recording since "head" does support really big numbers. This means that we have to precompute how many samples we want in the whole recording. Another problem with the large recordings is that some filesystems have a maximum file size of about two gigabytes. In particular, the author wanted to record to a USB thumb drive rather than the Raspberry Pi's SD card because it would be faster and easier to move the thumb drive to another computer in a different room instead of copying gigabytes of recordings over the home network. [9]

Even with a larger maximum file size in the Linux filesystem, it is not possible to put some long recording into one file. The solution is to split up the file into separate recordings. We don't want to stop and restart rtl_sdr because then we could miss something. We just want to separate the data stream into different files. If we record I and Q at 2,048,000 samples per second then one minute is 245,760,000 samples. Having separate recording files also makes it easy to jump to the middle of the recording if your SDR program doesn't support a "fast forward" into the middle of the recording. Putting this all together we end up with this command line:

```
rtl_sdr -f 145180000 -d 0 -s 2048000 -p 0 -g 0 – |
head  --bytes='$totalsamples |
split --bytes= 245760000 --suffix-length=2 \
--numeric-suffixes - '$rawfilename
```

Where 145,180,000 is the receiver frequency, 2,048,000 is the sampling rate, $totalsamples is the total number of samples that will be in the recording, and 245,760,000 is one minute's worth of samples. I have written a "rtlrecord.sh" script that creates a second script and schedules the execution of the second script at the appropriate time.

```
#!/bin/bash
#
# rtlrecord.sh - schedule a RTL dongle recording
#
# (c) Copyright 2016 Douglas Quagliana KA2UPW
#
# Usage:  rtlrecord satellite-name hh:mm mm/dd/yyyy
#                   minutes-to-record filename-to-record-to
#
if [ -z "${5}" ]; then
    echo Usage:  $0 " satellite-name  hh:mm  mm/dd/yyyy  minutes-to-
record filename-to-record-to"
    exit
fi

# Two meter satellite subband is 145.8 to 146.0 MHz but here we
# just record the whole two meter band
# at maximum sampling.  This has several advantages: we get
# everything on two meters including all of
# the satellites that we can hear above the horizon, we get
# the APRS network on 144.390 and we don't
# have to worry about what the exact ppm error is on the
# frequency.  We also pick up nearby repeaters
# and everything else on two meters.
# Record at max sampling rate for several reasons: this lowers
# the noise on the desired signs, gives us
# more samples to work with to extend the significant bits
# beyond the 8-bit ADC, and (the best reason
# of all to record the half of the two-meter band: because we can).

samplingrate=2048000        # maximum sampling rate for RTL dongle.
                            # Any higher and the dongle starts to
                            # drop samples
donglenumber=0              # RTL dongle number
gain=0                      # gain to be used 0=automatic-gain
ppm=0                       # ppm correction
destinationfolder=/usbdrive # destination folder (probably needs to
                            # be a command line parameter)
```

```
# number of samples per minute (the "2" is I and Q);
# let is required here
let bytesinoneminute=60*$samplingrate*2

# minutes*(60sec/min)*samplingrate*2 (the "2" is I and Q);
# let is required here
let totalsamples=$4*60*$samplingrate*2

centerfreq=145180000 # for amateur satellites
#centerfreq=137500000 # for weather satellites


# Build the script that we will give to the "at" command
# for running "at" a specific time
# The script will look something like this:
#
# build the filename for the script and the raw recording
filename=$(basename "$0")
filename="${filename%.*}"

# user provides us with something like 12:34 01/23/2016
# but we want something like 20160123_1234 for the filenames
datetime=$3
YYYYMMDD=$(date --date=$datetime +%Y%m%d )
HHMM=$(echo $2 | tr -d ":")

# Use these names for amateur satellite recordings
shfilename="./"$filename"_"$1"_"$YYYYMMDD"_"$HHMM"Z.sh"
rawfilename=$destinationfolder"/"$1"_"$YYYYMMDD"_"$HHMM"Z_145180000Hz_
IQ_2048000SPS_min"
logfilename=$destinationfolder"/"$1"_"$YYYYMMDD"_"$HHMM"Z_145180000Hz_
IQ_2048000SPS.log"

# Create the script that will be sent to "at" to do
# the actual recording
echo '#!/bin/bash' > $shfilename
# script will log the starting time of the script to the logfile
echo 'echo Starting > '$logfilename >> $shfilename
# script will put the actual date/time into the logfile
echo 'date >> '$logfilename >> $shfilename

# Just record about half of the two meter band centered on about
# 145 MHz. We want APRS on 144.39 and the satellite subband at
# 145.8-146.0.  rtl_sdr -n parameter is uint32 so it won't take
# really big numbers. Use the "head" program to end the recording
# since it DOES supports really big numbers.
# split on 245760000 bytes is a split once a minute
#
# There are a couple of problems with recording at 2.048M SPS:
# -non-Unix filesystems like the kind you find on a regular USB
```

```
# drive have a maximum filesize of about 2GB. This is too small
# for some of the satellite passes.
# -rtl_sdr uses uint32 for -n so you can't tell rtl_sdr to
# record a huge file.
# -if you put everything in one file, and the interesting part
# is in the middle then you'll wait forever for one of the
# SDR software programs to "play" the recording to get to the good
# part. Splitting every minute lets you concatenate just the
# minutes you want and then run sox2wav
# on just those minutes.  This will also be useful later for blind
# searches - easier to parallelize on smaller piecemeal recordings.
#

# for 2m amateur use this (for weather satellites change frequency)
echo 'rtl_sdr -f 145180000 -d '$donglenumber '-s '$samplingrate '-p
'$ppm '-g '$gain ' - | \' >> $shfilename
echo 'head  --bytes='$totalsamples ' | \'
>> $shfilename
echo 'split --bytes='$bytesinoneminute' --suffix-length=2 --numeric-
suffixes - '$rawfilename  >> $shfilename

echo 'echo Ending >> '$logfilename >> $shfilename
# script will put the actual date/time into the logfile
echo 'date >> '$logfilename >> $shfilename

# Note: the .sh file we are creating needs to be on a *ix
# filesystem in order for us to run chmod on it.  If you put
# the .sh file onto the usbdrive you cannot chmod it.
#
chmod a+x $shfilename
#
# Schedule the script to run at the right time
at $2 $3 -f $shfilename
```

The final “at” line will schedule the execution of the script that was just created. At the appropriate time the recording will be started and then stopped on the RTLSDR dongle. With luck, it contains the audio from the satellite of interest.

What could be better? Future Work (a.k.a. Here’s what I need help with…)

How about a phased array of multiple RTLSDR dongles? Recently the hardware side of this became much easier with the new V3 dongles that rtlsdr.org sells online. Why phased array of RTLSDR dongles? Why RTLSDR dongles? First, these receivers are extremely cheap. Second, at two megasamples per second I/Q sampling, we easily get the entire two meter satellite subband (or any two megahertz of the 70cm band). With the phased array we get several additional advantages. Combining multiple signals gives up gain over a single RTLSDR. By phasing the signals (in software) we can create directional reception beams (beamforming) to listen with gain in a particular direction. We can do this in real time,

or we can record the signals from all of the RTLSDR dongles (e.g. with a Raspberry Pi or two) and then do the beamforming later on a machine with a faster processor.

With SDR IQ recordings we can rerun the beamforming again but point the reception beam in a different direction. We can re-run the processing on the recordings multiple times with different beams on the same recording. This means we can record the two meter satellite subband once then reprocess it as many times as we want to extract as many satellite signals as we want. Suppose two or more satellites were above the local horizon at the same time. With a steerable Yagi you have to choose one or the other in real time and that choice is fixed forever. You can't decide later that you really wanted to listen in a different direction to a different satellite. With recordings from a phased array you can point (and steer) a beam at both. You can go back in time and rerun the pass pointing in a different direction. A (huge) archive of SDR recordings also gives us archeological capabilities. Was this satellite transponder ON last Tuesday at 0400Z?

There are still a few complications, because even with the sampling clocks synchronized, the phase of the local oscillators on the individual dongles will vary, but can be corrected in software once known. A proof of concept of using three dongles in a phased array has already been demonstrated [10].

The author welcomes comments, constructive criticism, and copies of your recordings from the Fox satellites.

Footnotes

[1] Finding Veronica – well, because Nemo and Dory were already found by Walt.

[2] Guinness, Alec, actor. *Star Wars: Episode VI - Return of the Jedi*. 1983. Lucasfilm, 1983.

[3] Deleted

[4] Apologies to Bill and Jules.

[5] Using the APRS on air signal as test signals to verify that everything is working correctly was inspired by a technique used by the SETI@home project. They inject test signals into the telescope receiver to verify that their hardware and software are working as expected. Compare the APRS signal waterfall to figure 2 at https://setiathome.berkeley.edu/sah_sci_newsletters.php?frag=news-6.inc

[6] Buxton, Jerry, N0JY. [The] Little Girl that lives aboard AO-85. amsat-bb mailing list. June 30, 2016. http://www.amsat.org/pipermail/amsat-bb/2016-June/059326.html

[7] "I Get I (and Q recordings) with a little help from my friends"

[8] https://github.com/michelinok/sdrrecoder/blob/master/sdrrecorder.sh

[9] "Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway." Tanenbaum, Andrew S. *Computer Networks*, 4th ed., p. 91.

[10] "rtl_coherent: Synchronized RTL-SDR receivers". https://github.com/tejeez/rtl_coherent

AMSAT Engineering Documentation Update

Compiled by Jerry Buxton, N0JY
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AMSAT, as an educational organization, would like to publicly release the majority of our design documentation to serve as a learning tool to anyone interested in satellite development. However, in order to avoid complications with ITAR and Export Administration Rules, the information must first be released via an openly available publication. We would also like to be able to discuss our satellite projects with our own members, some of whom are not "US-persons" per those regulations. These AMSAT Space Symposium proceedings provide a convenient mechanism for the needed publication in order to make this information public domain and allow us to communicate with our members.

While many of the Fox-1 documents were published in previous *Proceedings*, some of these documents have undergone changes as the satellite design has progressed and evolved therefore the updated versions will be reproduced in these 2016 Space Symposium proceedings. In addition, these proceedings also present new engineering documents that have been produced since the last publication which include some of the documentation for the RadFxSat (Fox-1B) and RadxSat-2 (Fox-1E) satellites. Also included are some of the documents from the development of the Heimdallr (Phase 5) lunar orbiting satellite.

Fox-1 Documents

This section contains the final RadFxSat (Fox-1B) ICD (Interface Control Document) for the Vanderbilt University ISDE experiment (**page 57**). The control of the RadFxSat experiment is essentially the same as that of the Fox-1A Vanderbilt experiment. Also included for RadFxSat are an updated avionics bus pin assignment (**page 73**), and a CAD drawing of the avionics stack (**page 85**).

One document is included for Fox-1Cliff and Fox-1D, which details the resolution calculations for the Virginia Tech camera experiments (**page 87**). These calculations were necessary in the application for the NOAA imaging licenses.

The Fox-1E documentation includes the draft System Requirements (**page 95**), Downlink Specification for the telemetry being sent (**page 105**), a document describing the use of average power tracking for the Fox-1E linear transponder (**page 123**), a schematic of the mixers and IF for the Fox-1E transponder (**page 129**), and a document describing a 1200 bps BPSK modulator for the Fox-1E transponder (**page 131**).

Heimdallr (Phase 5 / CubeQuest Challenge) Documents

This section contains several link budget calculations used in the planning and design for the Heimdallr lunar orbiting satellite (Phase 5) (**page 137**).

Date: December 16, 2015
Version: Version 1.01

AMSAT *Fox-1B (RadFxSat)*

IHU to Experiment 1 Interface Control Document

1 Introduction

This document specifies the message interface between the Internal Housekeeping Unit (IHU) and the Experiment System in Position 1 of the satellite, known as the Vanderbilt University Phoenix Payload and abbreviated herein as EXP1.

1.1 Document History

DATE	VERSION	SUMMARY
December 15, 2015	1.00	Initial version
December 16, 2015	1.01	Change Vulcan to Phoenix

1.2 Document Scope

This document will specify the control of EXP1, the messaging format, and the I²C bus hardware operation for the communications between the IHU and the EXP1.

1.3 References

1. AMSAT *Fox-1,* System Requirements Specification
2. AMSAT *Fox-1*, System Design Specification
3. AMSAT *Fox-1*, IHU Software Architecture Specification
4. Vanderbilt University Phoenix Payload Interface Control Document

2 General Messaging Requirements

2.1 Link Protocol Requirements

2.1.1 The IHU shall initiate a command to the EXP1.

2.1.2 The EXP1 shall send a reply to each IHU request.

2.1.3 Message bit order shall be Big Endian.

2.1.4 The IHU shall determine the action to be taken in the event of an invalid, improper, or missing message from the EXP1.

2.1.5 The EXP1 shall take no action in the event of an invalid or improper message from the IHU.

2.1.6 Message byte order shall be Big Endian.

2.2 General Message Requirements

2.2.1 Each message shall contain a header block.

2.2.2 Each message shall contain a packet error check (PEC) in the form of CRC8.

2.2.2.1 The message address byte shall be included when calculating the CRC8.

2.3 I²C 1 Bus Hardware Interface Requirements

2.3.1 The I²C Vdd shall be 3.0V.

2.3.2 The bus speed shall be Fast (400kbit/s).

2.3.3 The EXP1 I²C 7 bit address shall be 0x2A.

3 Experiment Operation

3.1 Experiment Power Control

3.1.1 The IHU shall exert control over the power state of the EXP1 by the Experiment Enable 1 pin on the satellite bus as shown in Table 1.

Table 1

Pin State	Description
High	Power On Experiment
Low or high-impedance	Power Off Experiment

3.1.2 The IHU shall not power on the experiment if the power bus voltage (VBATT) is less than or equal to 3.3 Volts.

3.1.3 The IHU shall perform the Experiment Cease Operation Sequence and the Experiment Power Off Sequence if the power bus voltage (VBATT) falls to less than or equal to 3.3 Volts while the experiment is powered on.

3.2 Experiment Power On Sequence

3.2.1 The IHU shall set and hold the Experiment Enable 1 pin HIGH.

3.2.2 The IHU shall not send any message to the EXP1 for a minimum of 100 milliseconds.

3.2.3 The IHU shall send a Set Time command to the EXP1.

3.3 Experiment Begin Operation Sequence

3.3.1 Upon completion of the Power On sequence the IHU shall send a Set Run State Active command message to the EXP1.

3.4 Experiment Cease Operation Sequence

3.4.1 The IHU shall send a Set Run State Halt command message to the EXP1.

3.4.2 The IHU shall not send any message to the EXP1 for a minimum of 10000 milliseconds.

3.4.3 The IHU shall send a Set Run State Standby command message to the EXP1.

3.4.4 The IHU shall send the command message “0x05 0x00 0x00 0x01 0x00 0x01 (opcode=0x0500, arg1=0x0001, arg2=0x0001)” to the EXP1.

3.4.5 The IHU shall send the following series of command messages to the EXP1:

- “0x05 0x00 0x00 0x5C 0x00 0x00 (opcode=0x0500, arg1=0x005C, arg2=0x0000)”

- "0x05 0x00 0x00 0x5D 0x00 0x00 (opcode=0x0500, arg1=0x005D, arg2=0x0000)"
- "0x05 0x00 0x00 0x5E 0x00 0x00 (opcode=0x0500, arg1=0x005E, arg2=0x0000)"
- "0x05 0x00 0x00 0x5F 0x00 0x00 (opcode=0x0500, arg1=0x005F, arg2=0x0000)"
- "0x05 0x00 0x00 0x60 0x00 0x00 (opcode=0x0500, arg1=0x0060, arg2=0x0000)"
- "0x05 0x00 0x00 0x61 0x00 0x00 (opcode=0x0500, arg1=0x0061, arg2=0x0000)"
- "0x05 0x00 0x00 0x62 0x00 0x00 (opcode=0x0500, arg1=0x0062, arg2=0x0000)"
- "0x05 0x00 0x00 0x63 0x00 0x00 (opcode=0x0500, arg1=0x0063, arg2=0x0000)"

3.5 Experiment Power Off Sequence

3.5.1 The IHU shall set the Experiment Enable 1 pin LOW.

3.5.1.1 The absence of a HIGH state on the Experiment Enable 1 pin shall be construed as a LOW state whether the pin is actually LOW, or in a high-impedance state.

4 Message Content Requirements

4.1 Command Message

4.1.1 The message header block shall be constructed as shown in table 2.

4.1.2 The message header block shall be sent with each Command and Response block.

Table 2

Field	Size (Bytes)	Type	Min Value	Max Value	Description
Message Version	2	Unsigned	0x01	0xFFFF	Message ICD version
Software Build	2	Unsigned	0x01	0xFFFF	Software Build version

4.1.2.1 The Message Version shall be an integer representing the IHU to EXP1 ICD document version number from which the message format is derived, having the decimal point removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.1.2.2 The Software Build shall be an integer representing the software build version number of the system originating the message, having any decimal points removed (e.g. version 1.03 would be 103 decimal or 0x67).

4.2 Command Message Block

4.2.1 The command message block shall be constructed as shown in Table 3.

Table 3

Field	Size (Bytes)	Type	Min Value	Max Value	Description
COMMAND	2	Unsigned	0x0000	0x0280	Hexadecimal Command
ARGUMENT	Variable	Unsigned	-	-	Optional Arguments As Required

The command message block shall contain one command in the COMMAND field as shown in Table 4.

Table 4

Command Name	Size (Bytes)	Type	Min Value	Max Value	Description
Nop	2	Unsigned	0x0000	0x0000	No effect; response undefined. Test for I²C acknowledgement only.
Echo	2	Unsigned	0x0001	0x0001	Echo this byte stream
Resend	2	Unsigned	0x0002	0x0002	Resend last result
Get UID	2	Unsigned	0x0003	0x0003	Controller 7 byte identifier
Get Status	2	Unsigned	0x0004	0x0004	Controller status indication
Get Diagnostics	2	Unsigned	0x0006	0x0006	Self-check Diagnostic
Get Telemetry	2	Unsigned	0x0010	0x0010	Send telemetry data
Set Run State	2	Unsigned	0x0080	0x0080	Enter specified Run State
Get Run State	2	Unsigned	0x0081	0x0081	Query current Run State
Set Time	2	Unsigned	0x0100	0x0100	Number of seconds since epoch
Get Time	2	Unsigned	0x0101	0x0101	Number of seconds since epoch
Get Data	2	Unsigned	0x0280	0x0280	Send (number of bytes) data

4.2.3 The command message shall contain arguments for the Echo command, as shown in Table 5.

Table 5

Field	Size (Bytes)	Type	Min Value	Max Value	Description
ARGUMENT	4	Unsigned	-	-	Data to be echoed

4.2.4 The command message shall contain one argument for the Set Run State command, as shown in Table 6.

Table 6

Run State	Size (Bytes)	Type	Min Value	Max Value	Description
STANDBY	2	Unsigned	0x0001	0x0001	Enter Standby State
ACTIVE	2	Unsigned	0x0003	0x0003	Activate Experiments
HALT	2	Unsigned	0x0005	0x0005	Terminate Experiments

4.2.5 The command message shall contain arguments for the Set Time command, as shown in Table 7.

Table 7

Argument	Size (Bytes)	Type	Min Value	Max Value	Description
IHU Reset Counter	16	Unsigned	0x00	-	Count of the number of IHU resets from non-volatile FRAM
MET Timestamp	32	Unsigned	-	-	MET timestamp (seconds since last IHU reset)

4.2.6 The command message shall contain arguments for the Get Data command, as shown in Table 8.

Table 8

Argument	Size (Bytes)	Type	Min Value	Max Value	Description
BYTES TO SEND	2	Unsigned	0x00	0x00FF	Number of bytes to send (1-256)

4.3 Response Message Block

4.3.1 The response message block shall be constructed as shown in Table 9.

Table 9

Field	Size (Bytes)	Type	Min Value	Max Value	Description
RESERVED	1	Unsigned	-	-	Reserved, ignore
ERROR CODE	1	Unsigned	0x0000	0x0006	Response to Command
LENGTH	2	Unsigned	0x00	0xFFFF	Length of Return Value in Bytes
RETURN VALUE	Variable	Variable	-	-	Return Value

4.3.2 The Error Code shall contain one code as shown in table 10.

Table 10

Name	Size (Bytes)	Type	Min Value	Max Value	Description
CMD_OK	1	Unsigned	0x0000	0x0000	Command invoked successfully
CMD_OP_ERR	1	Unsigned	0x0001	0x0001	Command not recognized
CMD_FORMAT_ERR	1	Unsigned	0x0002	0x0002	Incorrect command argument length
CMD_RANGE_ERR	1	Unsigned	0x0003	0x0003	Argument(s) out of bounds
CMD_PEC_ERR	1	Unsigned	0x0004	0x0004	Error check (CRC) mismatch
CMD_EXEC_ERR	1	Unsigned	0x0005	0x0005	Execution error
CMD_VERSION_ERR	1	Unsigned	0x0006	0X0006	Header Message Version mismatch

4.3.3 The Status Flags for a GET STATUS response message shall be represented as individual bit values of a 16 bit RETURN VALUE as shown in Table 11.

Table 11

Name	Bit Number	Description
REBOOTED	0	1 = Experiment has rebooted – **NOT USED**
DATA READY	1	1 = Experiment data available
TIME REQUEST	2	1 = Request SET TIME
FAILED RUN STATE	3	1 = Failed the run state – **NOT USED**
COMPLETED RUN STATE	4	1 = Completed the run state – **NOT USED**
RESERVED	5-15	Always 0

4.3.4 The response message to a Set Time command shall contain one of the values as shown in Table 12.

Table 12

Response Name	Size (Bytes)	Type	Min Value	Max Value	Description
SUCCESS	2	Signed	0x00	0x00	Time Set successfully
FAILURE	2	Signed	0xFFFF	0xFFFF	Time Set failed

5 Message Integrity

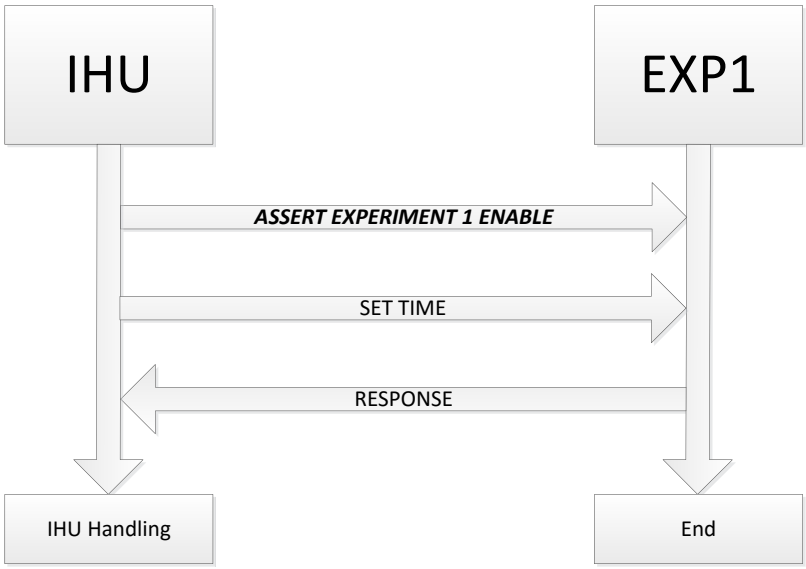
5.1 Invalid Messages

5.1.1 If the PEC (CRC8) fails, the message shall be considered invalid.

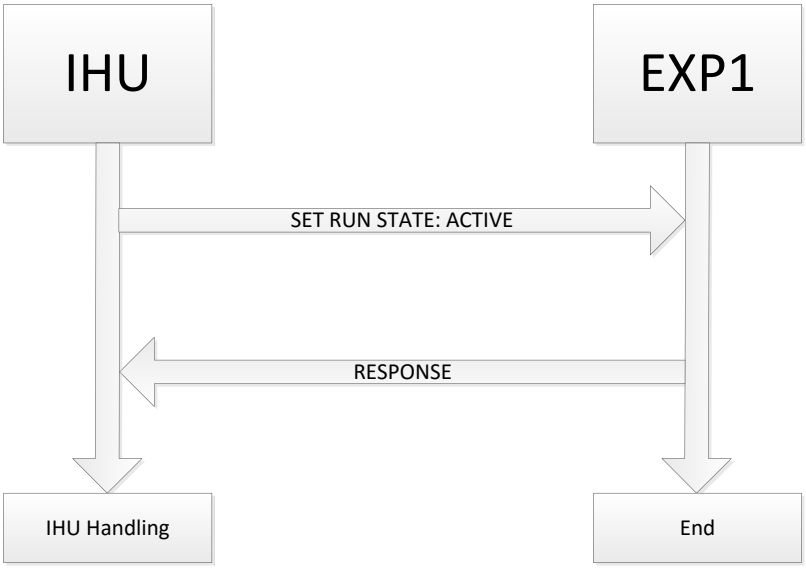
5.1.2 If the Message Version does not match the message version in use for the construction of messages on the receiving system, the message shall be considered invalid.

6 Message Flow Diagrams

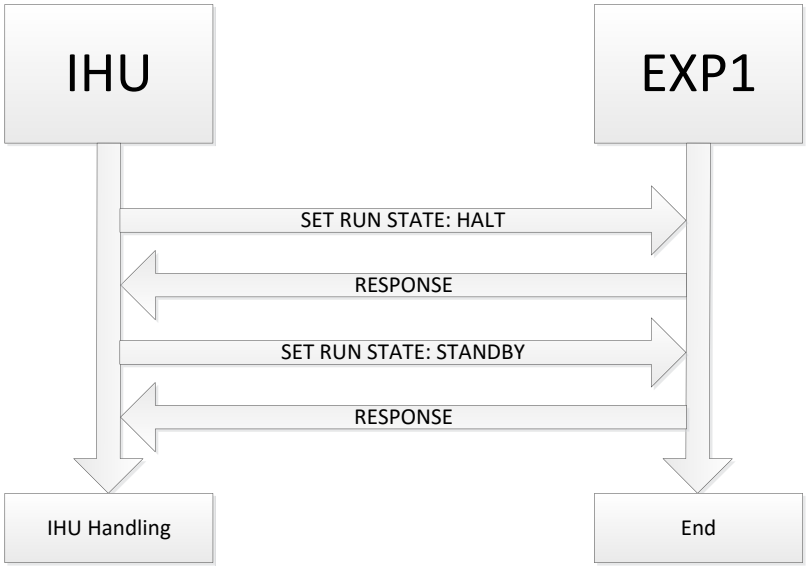
6.1 EXPERIMENT POWER ON SEQUENCE



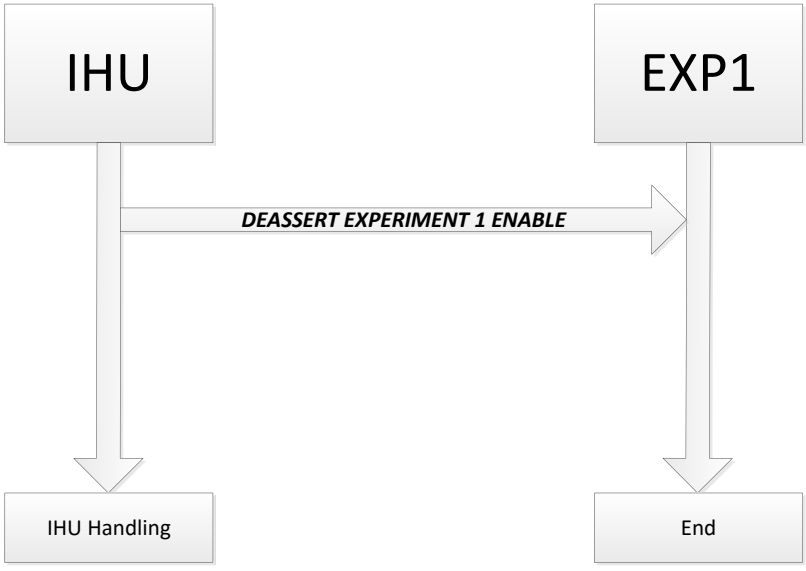
6.2 EXPERIMENT BEGIN OPERATION SEQUENCE



6.3 EXPERIMENT CEASE OPERATION SEQUENCE



6.4 EXPERIMENT POWER OFF SEQUENCE



6.5 SERVICING EXPERIMENT OPERATION

Figure 1

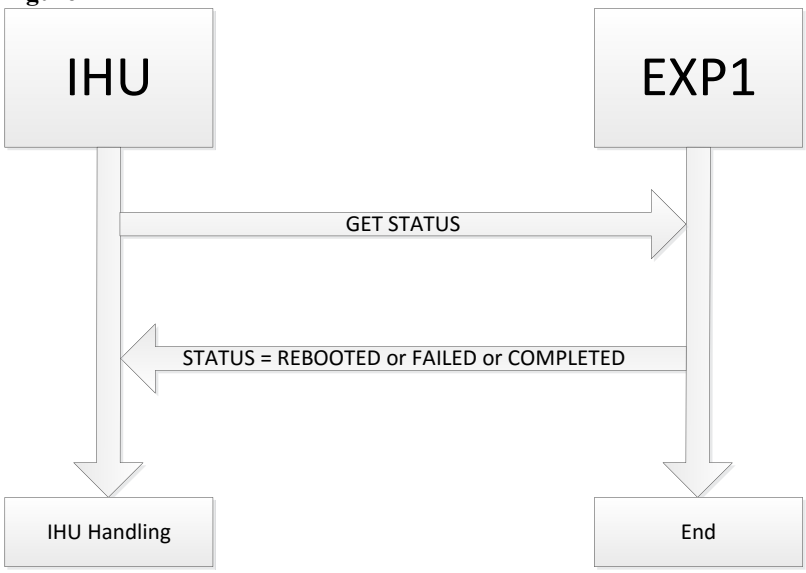


Figure 2

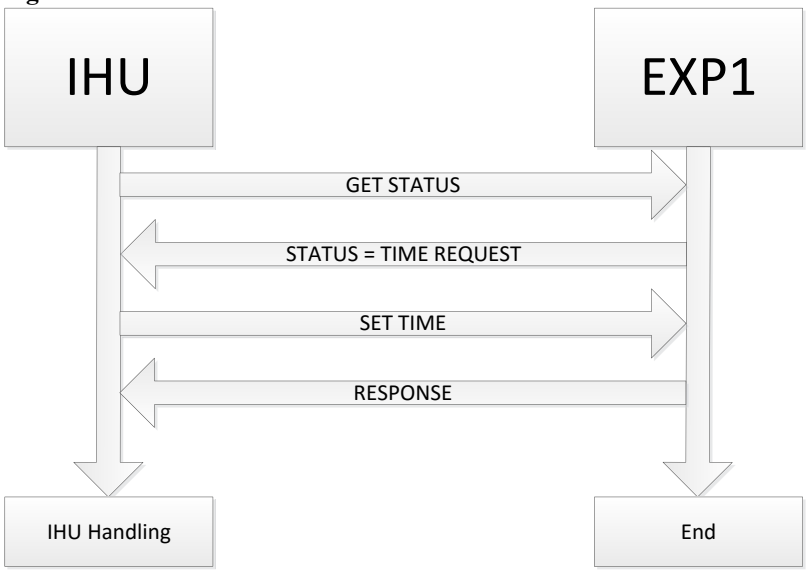
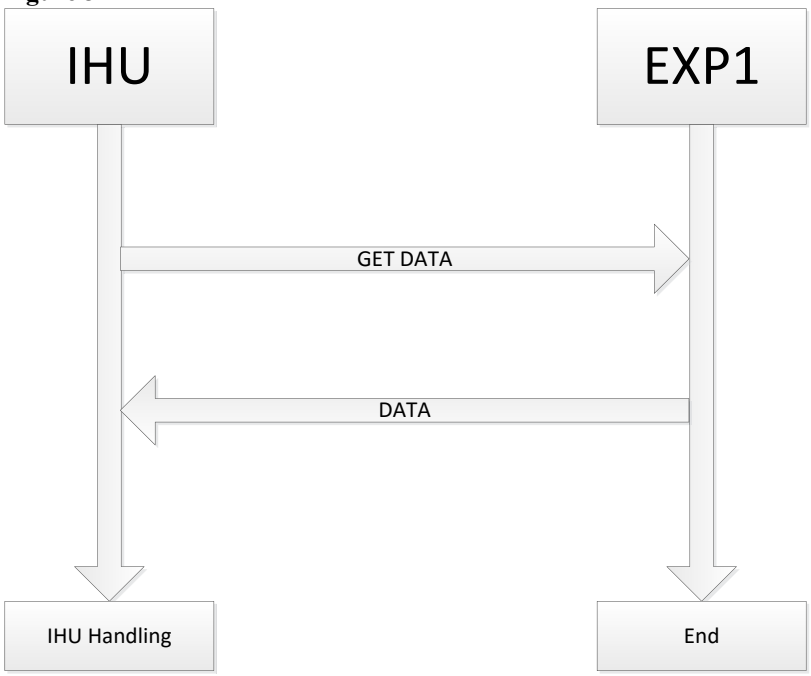
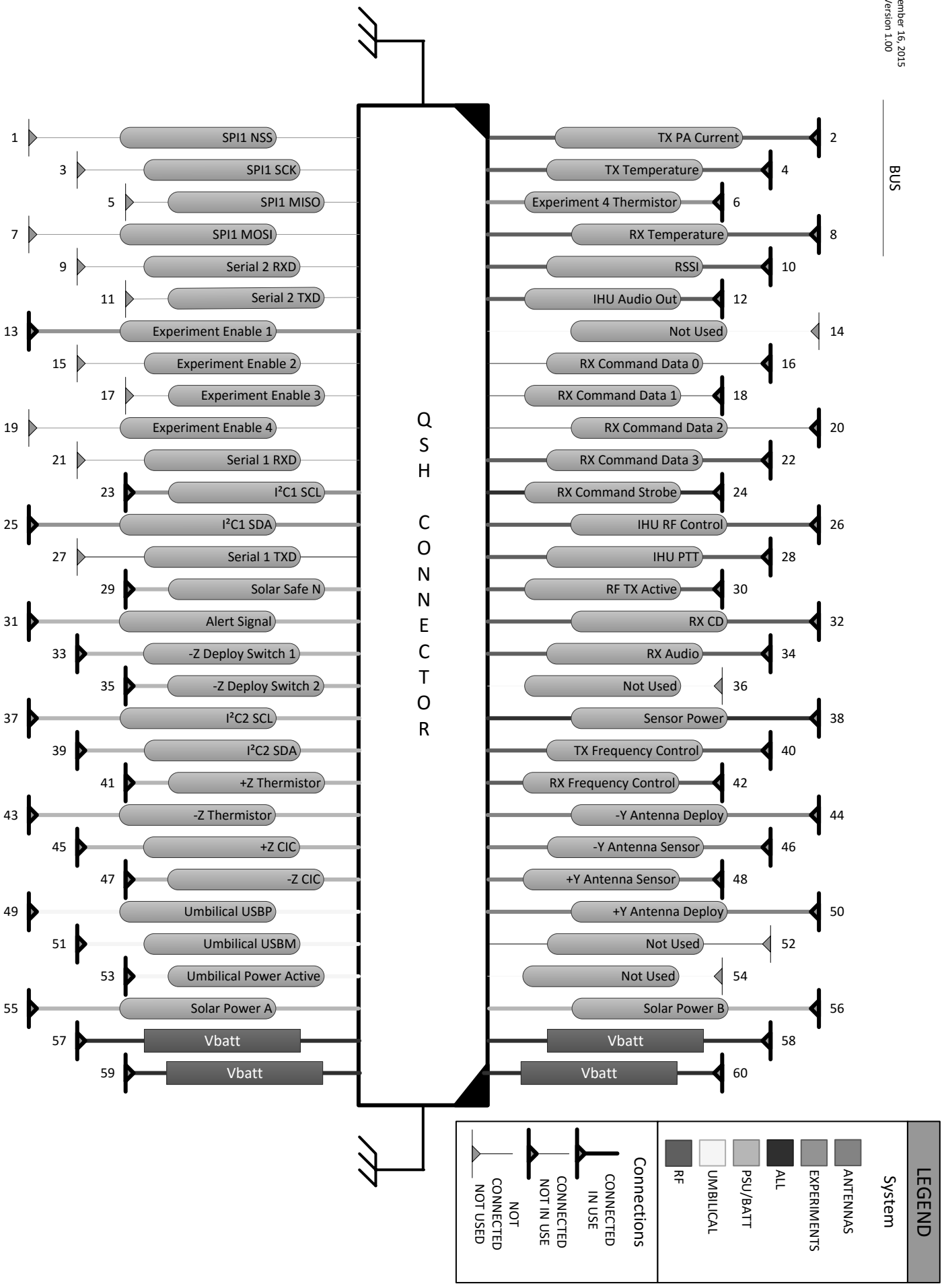


Figure 3



November 16, 2015
Version 1.00

BUS



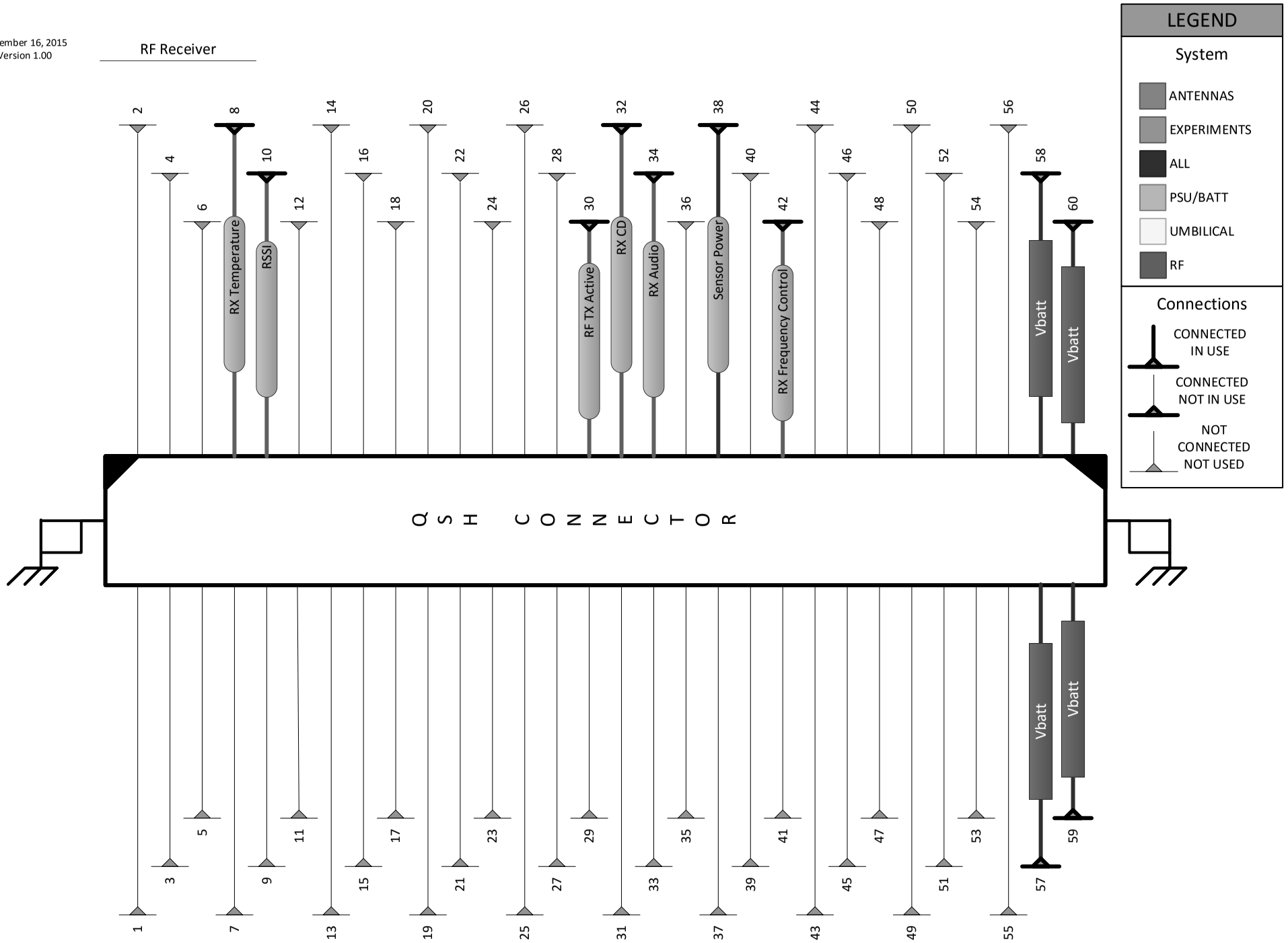
November 16, 2015
Version 1.00

November 16, 2015
Version 1.00

November 16, 2015
Version 1.00

November 16, 2015
Version 1.00

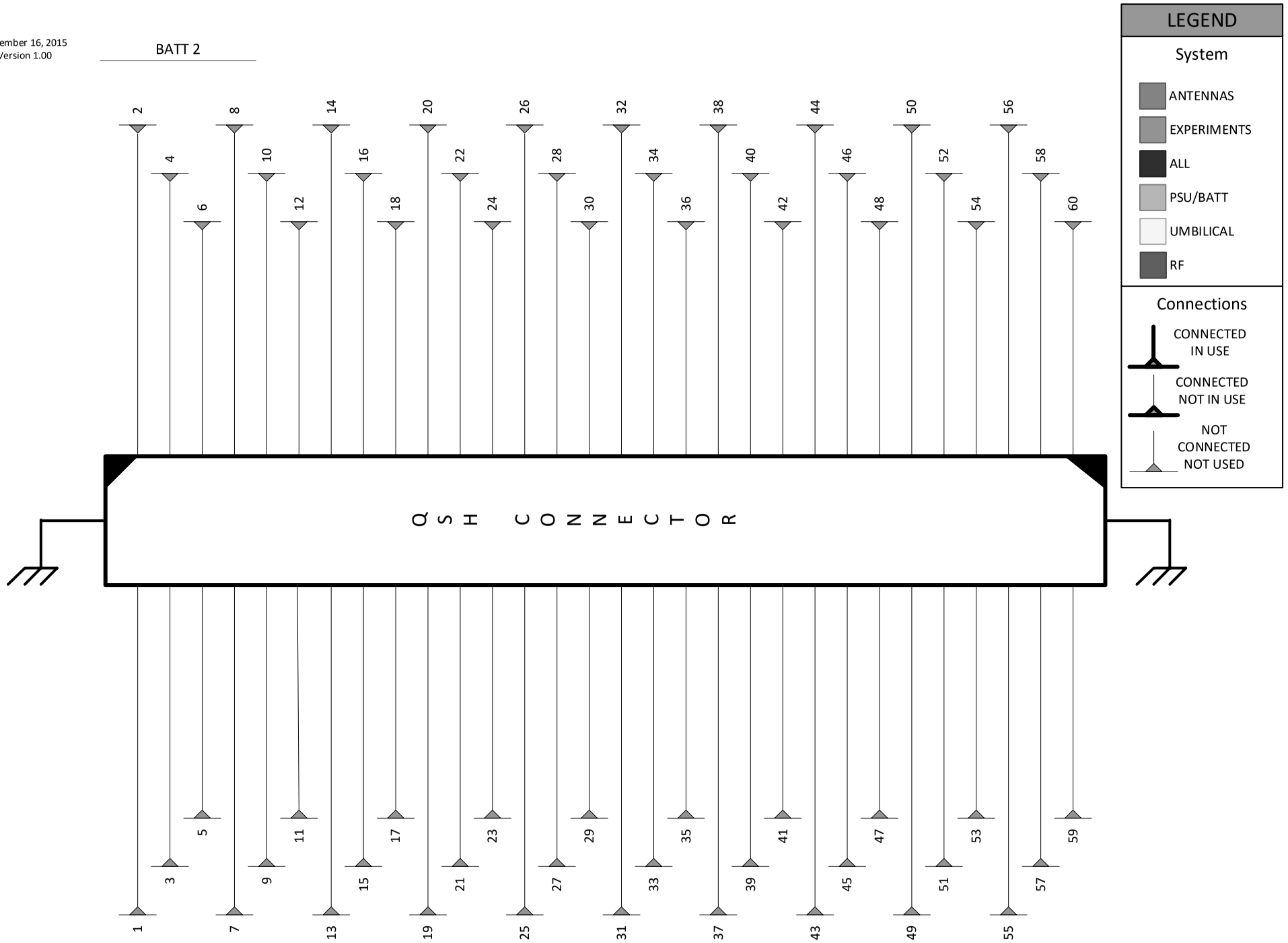
RF Receiver



November 16, 2015
Version 1.00

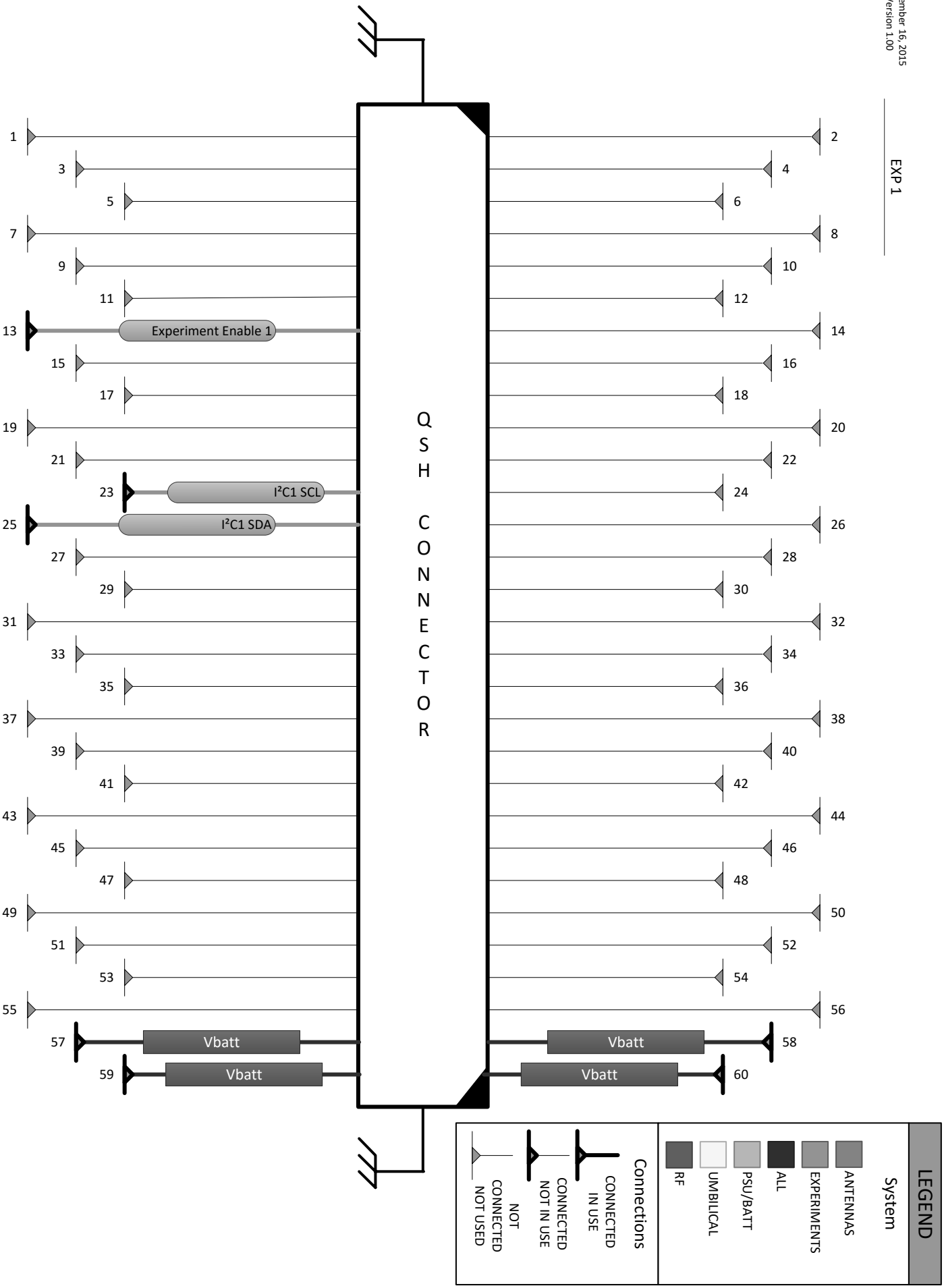
November 16, 2015
Version 1.00

BATT 2

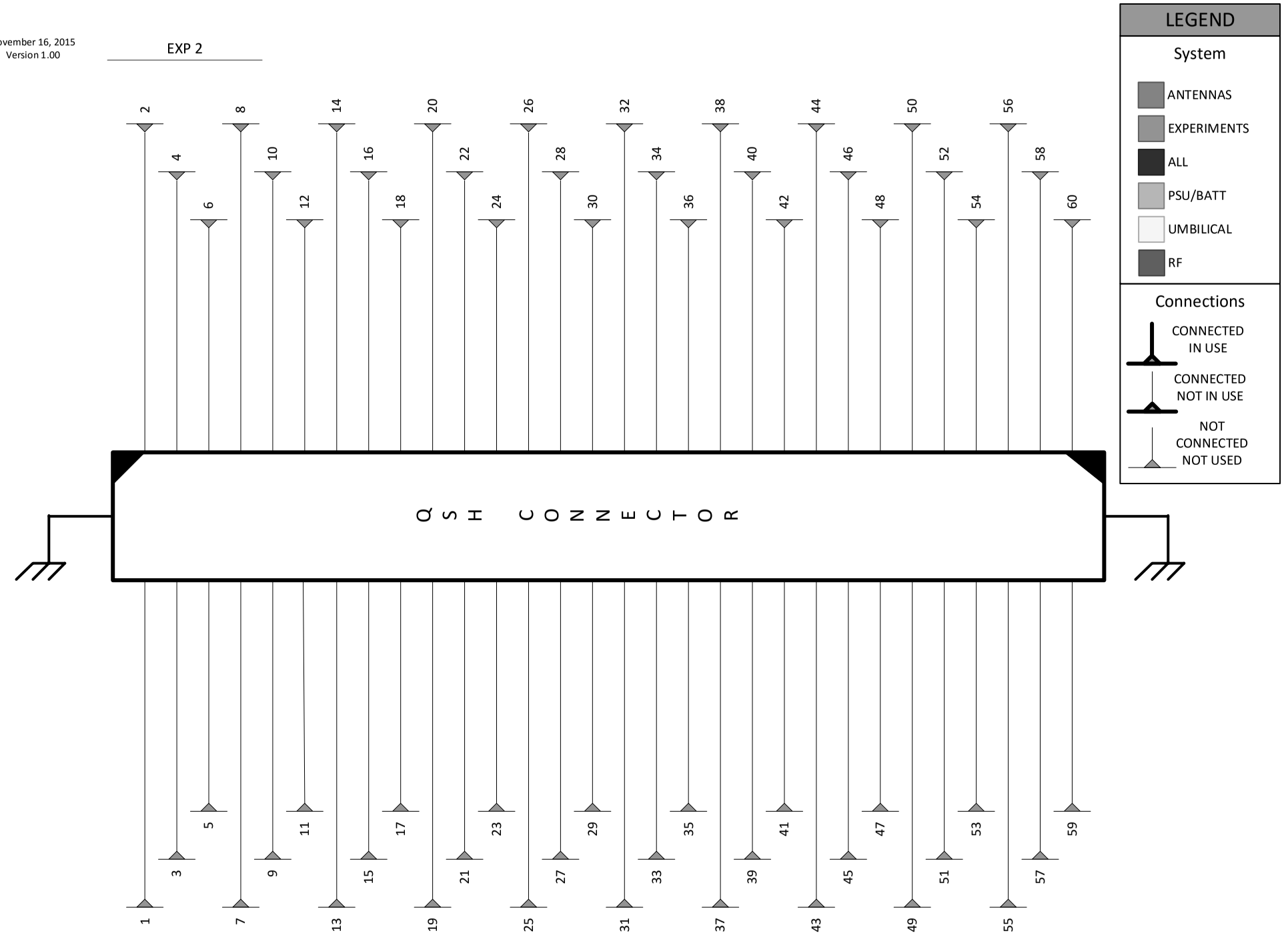

LEGEND
System
ANTENNAS
EXPERIMENTS
ALL
PSU/BATT
UMBILICAL
RF
Connections
CONNECTED IN USE
CONNECTED NOT IN USE
NOT CONNECTED NOT USED
QSH CONNECTOR
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59

November 16, 2015
Version 1.00

EXP 1

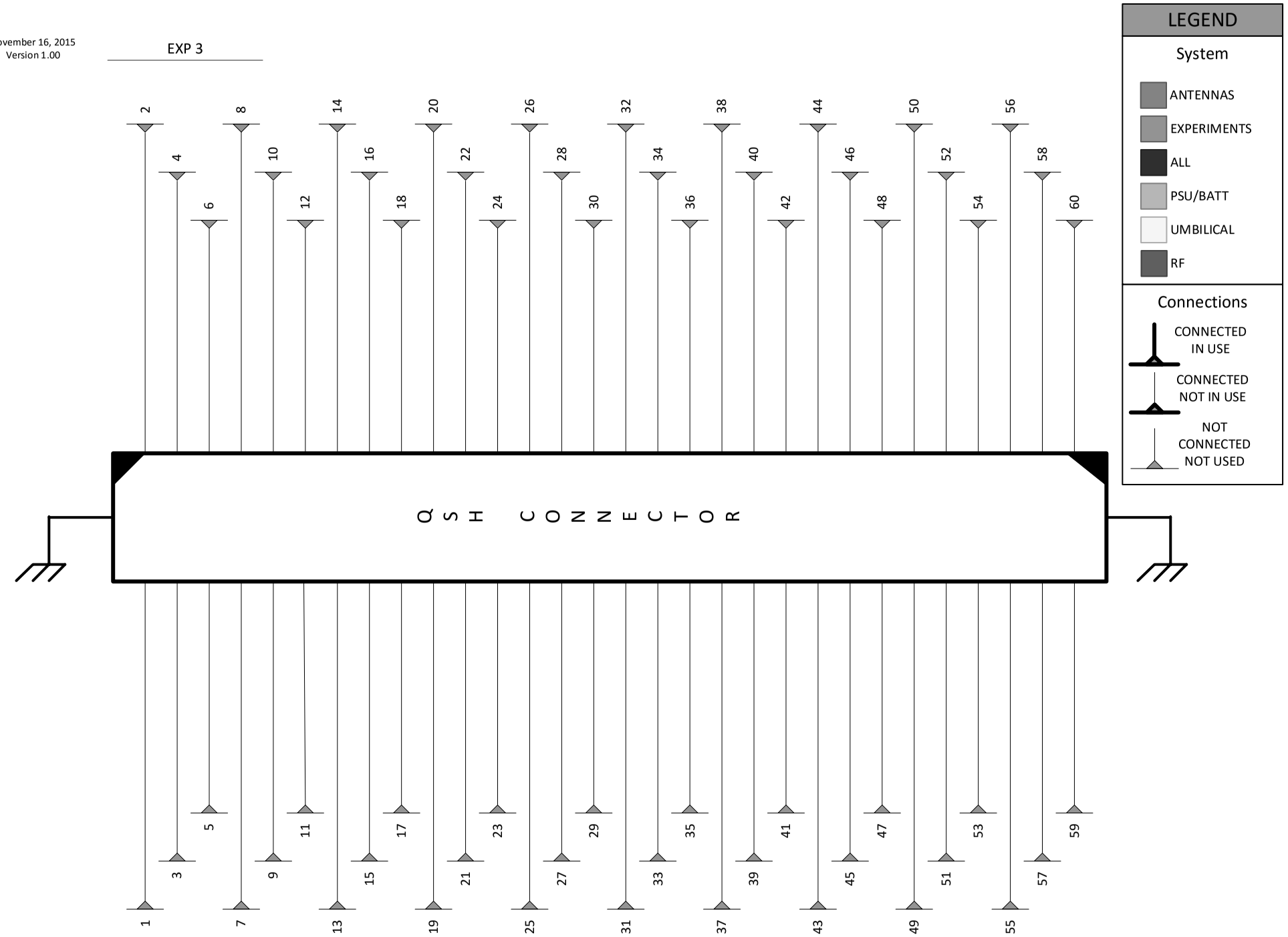


EXP 2

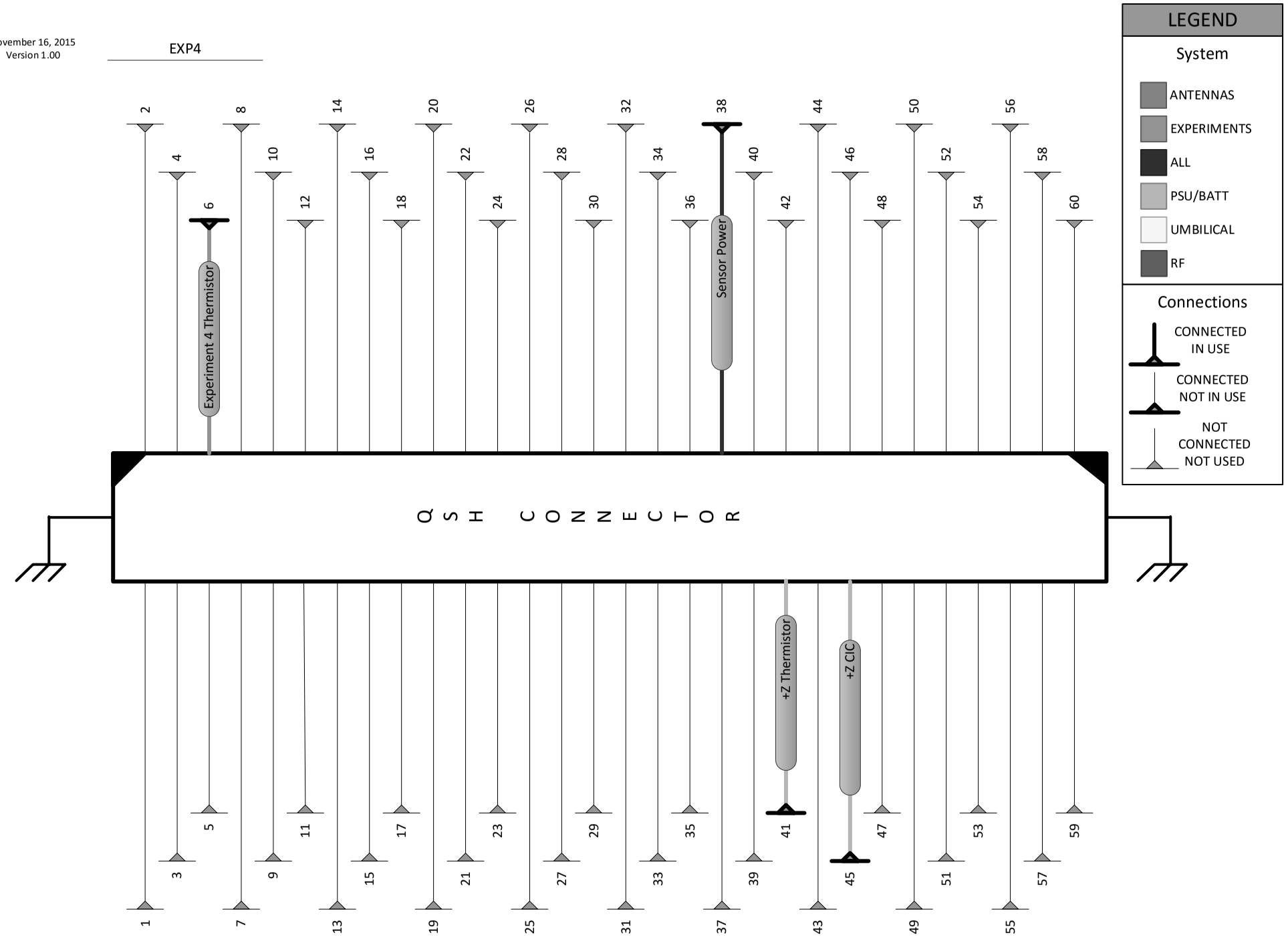

LEGEND
System
ANTENNAS
EXPERIMENTS
ALL
PSU/BATT
UMBILICAL
RF
Connections
CONNECTED IN USE
CONNECTED NOT IN USE
NOT CONNECTED NOT USED
QSH CONNECTOR
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59

November 16, 2015
Version 1.00

EXP 3


LEGEND
System
ANTENNAS
EXPERIMENTS
ALL
PSU/BATT
UMBILICAL
RF
Connections
CONNECTED IN USE
CONNECTED NOT IN USE
NOT CONNECTED NOT USED
QSH CONNECTOR
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59

EXP4


LEGEND
System
ANTENNAS
EXPERIMENTS
ALL
PSU/BATT
UMBILICAL
RF
Connections
CONNECTED IN USE
CONNECTED NOT IN USE
NOT CONNECTED NOT USED
Q S H C O N N E C T O R
Experiment 4 Thermistor
Sensor Power
+Z Thermistor
+Z CIC
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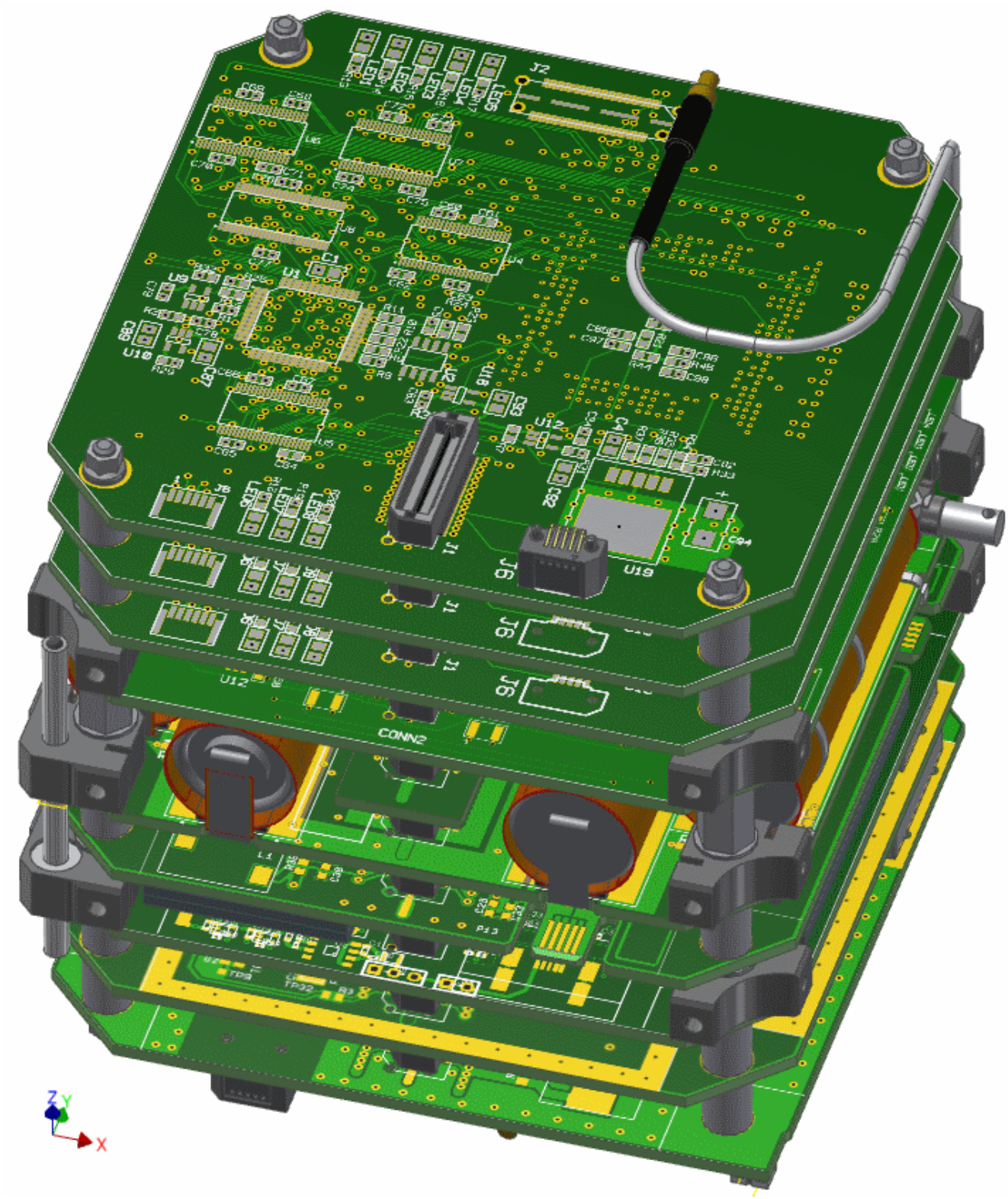


RadFxSat avionics stack

Given Data:

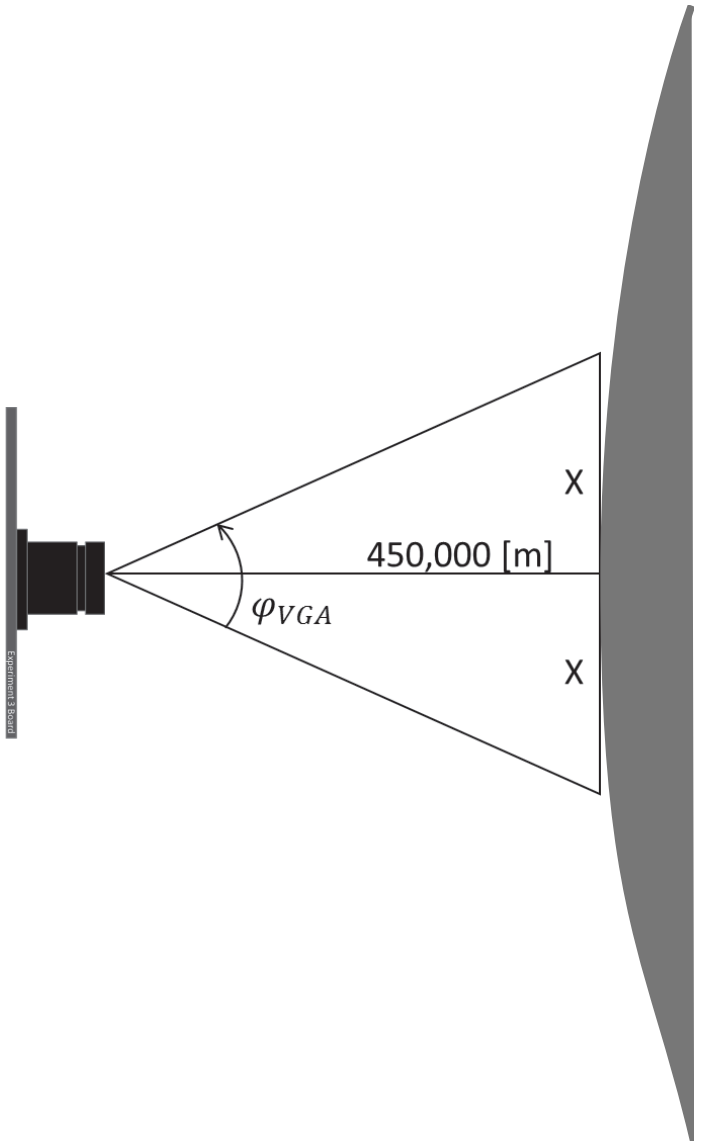
- Orbital Altitude = 450 km
- Calculation done for Perigee

Assumptions:

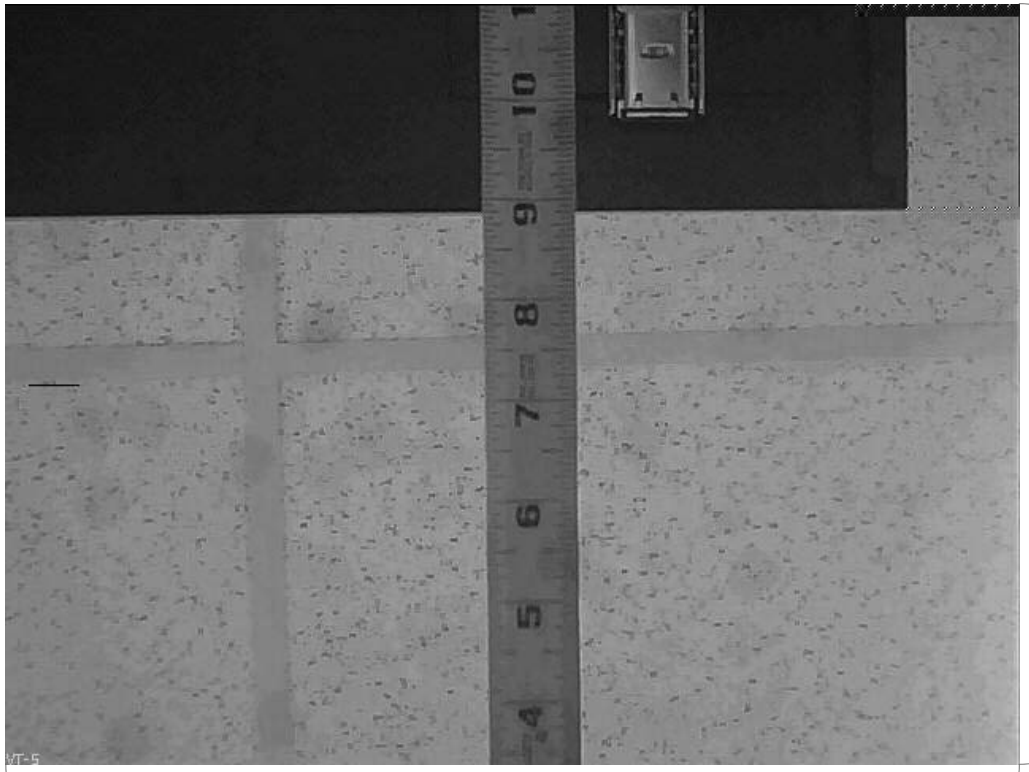
- Flat Earth: When accounting for curve of earth, resolution will decrease.

Goal:

- Determine Resolution of Camera at Perigee in VGA (640x480 pixels) Mode.
- Determine Resolution of Camera at Perigee in QVGA (320x240 pixels) Mode.



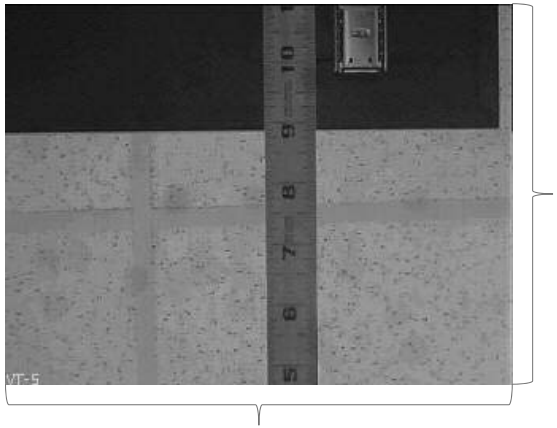
VGA Image:



480 pixels

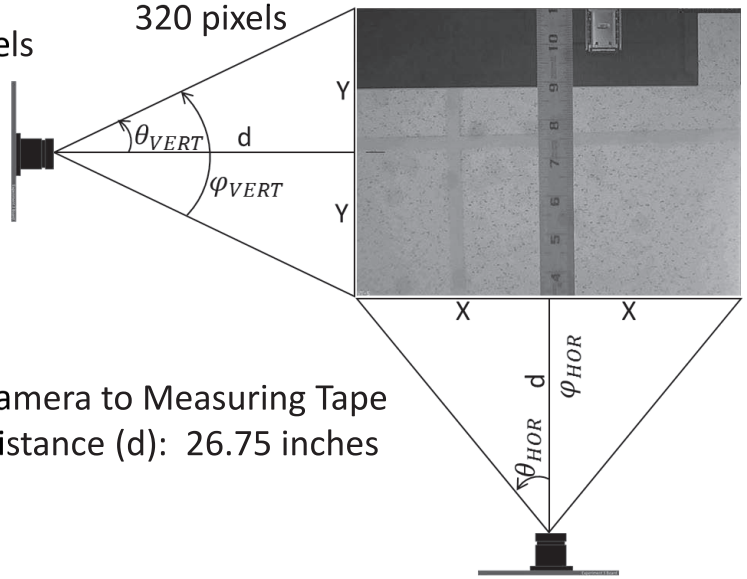
640 pixels

QVGA Image:



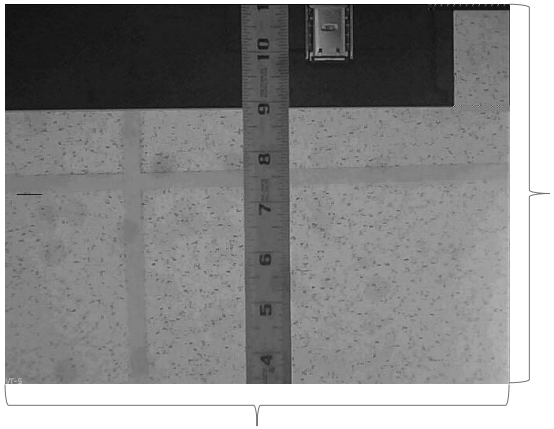
240 pixels

320 pixels



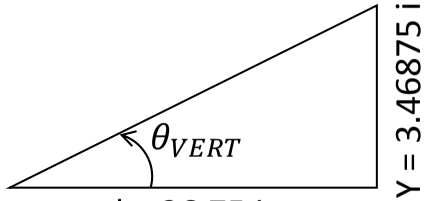
Camera to Measuring Tape Distance (d): 26.75 inches

VGA Image:

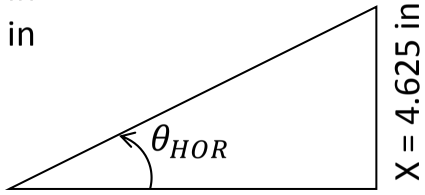


480 pixels
2Y = 6.9375 in
Y = 3.46875 in

640 pixels, 2X = 9.25 in, X = 4.625 in

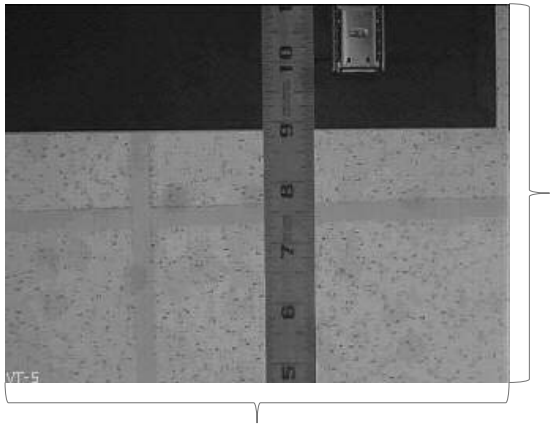


$$\theta_{VGA,VERT} = \tan^{-1}\left(\frac{3.46875}{26.75}\right)$$
$$\theta_{VGA,VERT} = 7.38848\ [deg]$$
$$\boldsymbol{\varphi_{VGA,VERT} = 2\theta_{VGA,VERT} = 14.777[deg]}$$



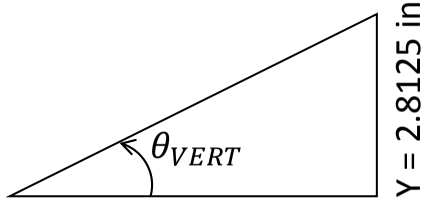
$$\theta_{VGA,HOR} = \tan^{-1}\left(\frac{4.625}{26.75}\right)$$
$$\theta_{VGA,HOR} = 9.8093\ [deg]$$
$$\boldsymbol{\varphi_{VGA,HOR} = 2\theta_{VGA,HOR} = 19.619[deg]}$$

QVGA Image:

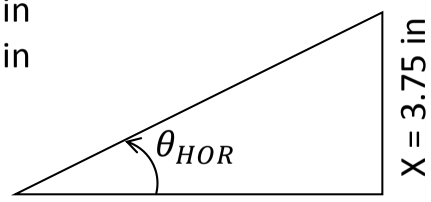


240 pixels
2Y = 5.625 in
Y = 2.8125 in

320pixels, 2X = 7.5 in, X = 3.75 in

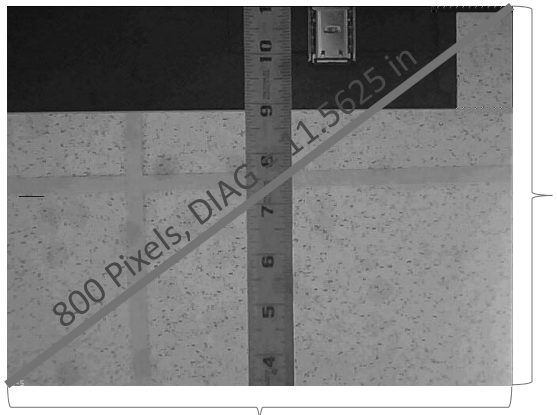


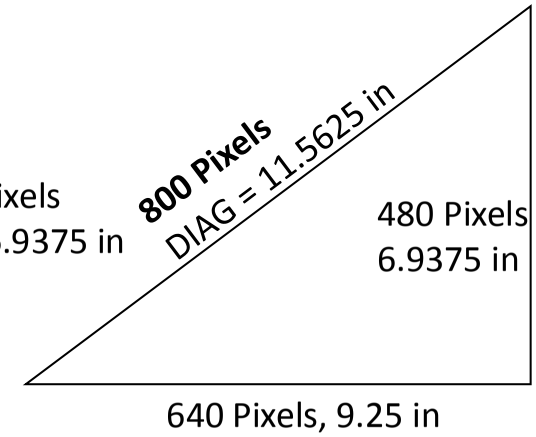
$$\theta_{QVGA,VERT} = \tan^{-1}\left(\frac{2.8125}{26.75}\right)$$
$$\theta_{QVGA,VERT} = 6.00204\ [deg]$$
$$\boldsymbol{\varphi_{QVGA,VERT} = 2\theta_{QVGA,VERT} = 12.004[deg]}$$

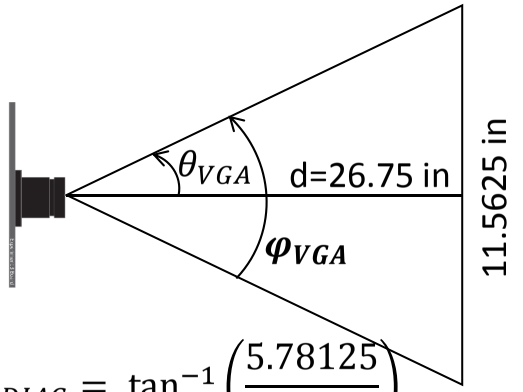


$$\theta_{QVGA,HOR} = \tan^{-1}\left(\frac{3.75}{26.75}\right)$$
$$\theta_{QVGA,HOR} = 7.98011\ [deg]$$
$$\boldsymbol{\varphi_{QVGA,HOR} = 2\theta_{QVGA,HOR} = 15.960[deg]}$$

VGA Image:





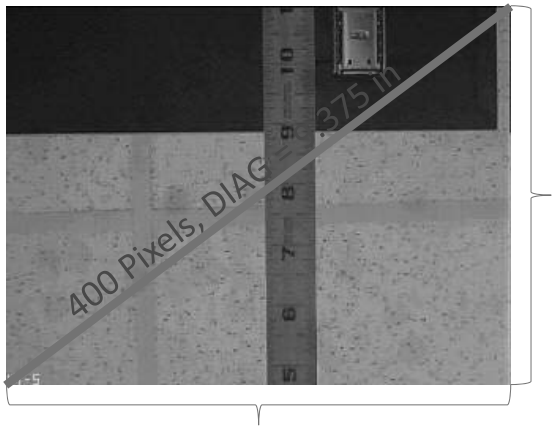


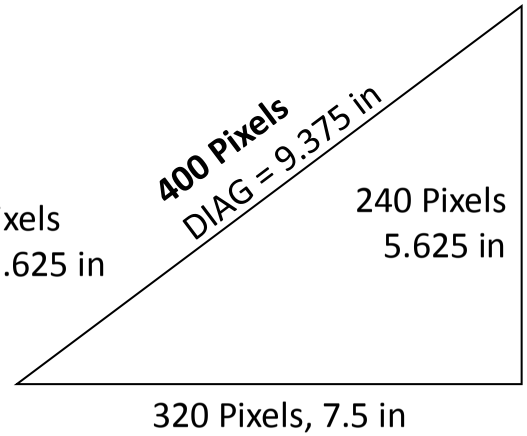
$$\theta_{VGA,DIAG} = \tan^{-1}\left(\frac{5.78125}{26.75}\right)$$

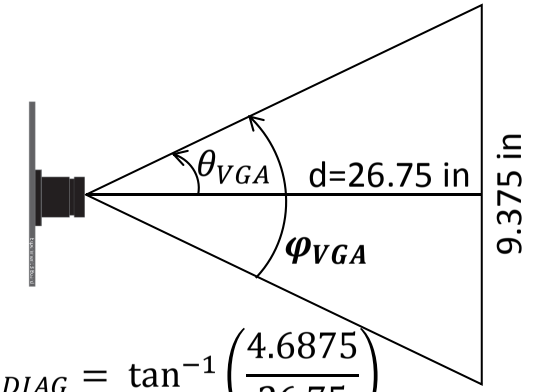
$$\theta_{VGA,DIAG} = 12.1953\ [deg]$$

$$\boldsymbol{\varphi_{VGA,DIAG} = 2\theta_{VGA,DIAG} = 24.391\ [deg]}$$

QVGA Image:





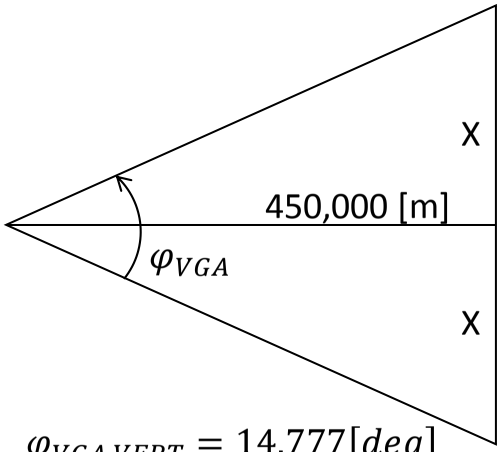


$$\theta_{QVGA,DIAG} = \tan^{-1}\left(\frac{4.6875}{26.75}\right)$$

$$\theta_{QVGA,DIAG} = 9.9392\ [deg]$$

$$\boldsymbol{\varphi_{QVGA.DIAG} = 2\theta_{QVGA,DIAG} = 19.879\ [deg]}$$

VGA Image:



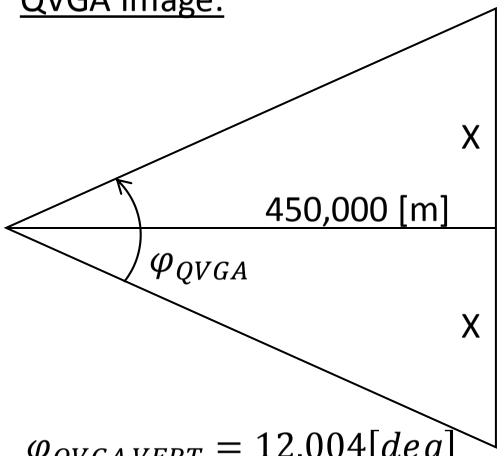
$\varphi_{VGA,VERT} = 14.777[deg]$

$$X = 450{,}000\ [m]\ * \tan\left({}^{\varphi_{VGA,VERT}}/_{2}\right)$$
$$= 58{,}353\ [m]$$
$$2X = \ 116{,}706[m]$$

CAM pixel res: 640 x 480 pixels
Vertical: $480\ [pixels]$
THUS:

$$RESOLUTION_{VGA,VERT} = \frac{116{,}706[m]}{480[pixels]} \cong \mathbf{243.138}\left[{}^{\boldsymbol{m}}/_{\boldsymbol{pixel}}\right]$$

QVGA Image:



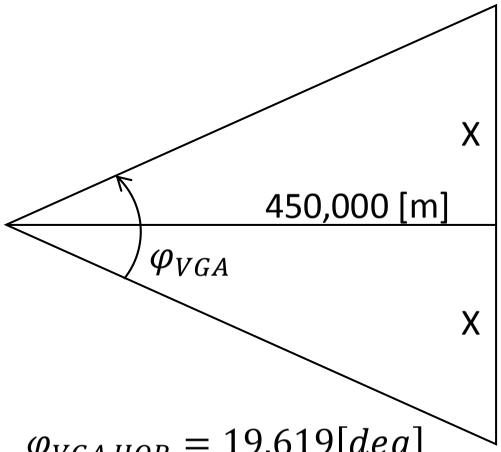
$\varphi_{QVGA,VERT} = 12.004[deg]$

$$X = 450{,}000\ [m]\ * \tan\left({}^{\varphi_{QVGA,VERT}}/_{2}\right)$$
$$= 47{,}312.8\ [m]$$
$$2X = \ 94{,}625.6\ [m]$$

CAM pixel res: 320 x 240 pixels
Vertical: $240[pixels]$
THUS:

$$RESOLUTION_{QVGA,VERT} = \frac{94{,}625.6\ [m]}{240[pixels]} \cong \mathbf{394.273}\ \left[{}^{\boldsymbol{m}}/_{\boldsymbol{pixel}}\right]$$

VGA Image:



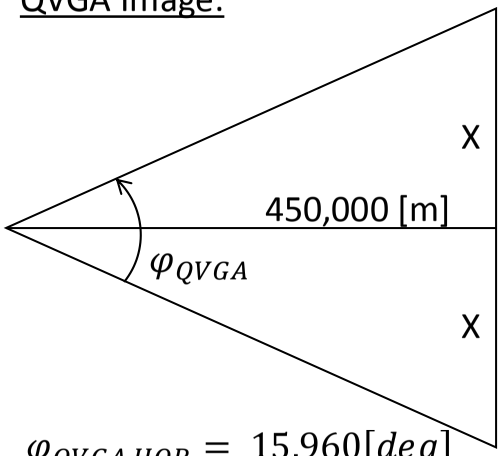
$\varphi_{VGA,HOR} = 19.619[deg]$

$$X = 450{,}000\ [m]\ * \tan\left({\varphi_{VGA,DIAG}}/{2}\right)$$
$$= 77{,}805.3\ [m]$$
$$2X = \ 155{,}611\ [m]$$

CAM pixel res: 640 x 480 pixels
Horizontal: 640 $[pixels]$
THUS:

$$RESOLUTION_{VGA,HOR} = \frac{115{,}611[m]}{640[pixels]} \cong \mathbf{243.142}\left[{\boldsymbol{m}}/{\boldsymbol{pixel}}\right]$$

QVGA Image:



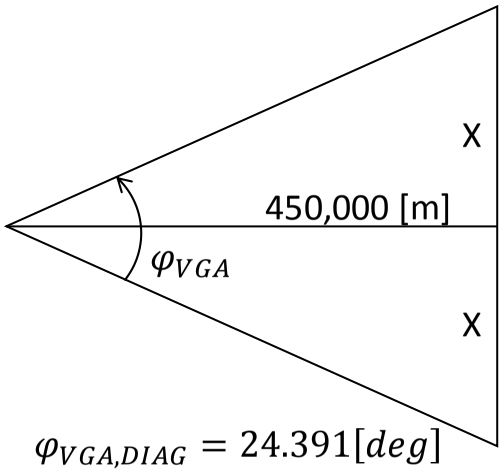
$\varphi_{QVGA,HOR} = 15.960[deg]$

$$X = 450{,}000\ [m]\ * \tan\left({\varphi_{QVGA,DIAG}}/{2}\right)$$
$$= 63{,}083.2\ [m]$$
$$2X = \ 126{,}166\ [m]$$

CAM pixel res: 320 x 240 pixels
Horizontal: 320 $[pixels]$
THUS:

$$RESOLUTION_{QVGA,HOR} = \frac{126{,}166\ [m]}{320[pixels]} \cong \mathbf{394.270}\ \left[{\boldsymbol{m}}/{\boldsymbol{pixel}}\right]$$

VGA Image:



$\varphi_{VGA,DIAG} = 24.391[deg]$

$$X = 450{,}000\ [m]\ * \tan\left({}^{\varphi_{VGA,DIAG}}/_{2}\right)$$
$$= 97{,}256.4\ [m]$$
$$2X = \ 194{,}513\ [m]$$

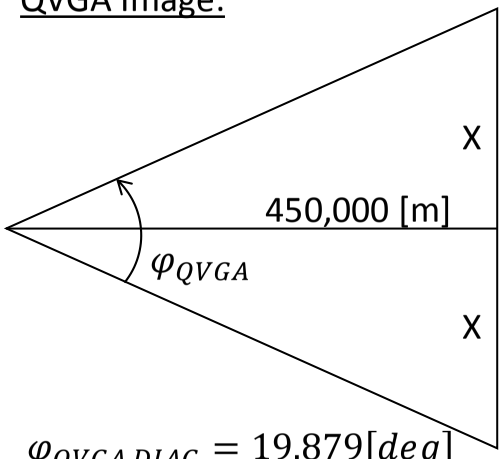
CAM pixel res: 640 x 480 pixels

Diagonal: $\sqrt{(640)^2 + (480)^2} = 800\ [pixels]$

THUS:

$$RESOLUTION_{VGA,DIAG} = \frac{194{,}509[m]}{800\ [pixels]} \cong \mathbf{243.141}\left[{}^{\boldsymbol{m}}/_{\boldsymbol{pixel}}\right]$$

QVGA Image:



$\varphi_{QVGA,DIAG} = 19.879[deg]$

$$X = 450{,}000\ [m]\ * \tan\left({}^{\varphi_{QVGA,DIAG}}/_{2}\right)$$
$$= 78{,}857.3\ [m]$$
$$2X = \ 157{,}715\ [m]$$

CAM pixel res: 320 x 240 pixels

Diagonal: $\sqrt{(320)^2 + (240)^2} = 400\ [pixels]$

THUS:

$$RESOLUTION_{QVGA,DIAG} = \frac{157{,}715\ [m]}{400\ [pixels]} \cong \mathbf{394.286}\ \left[{}^{\boldsymbol{m}}/_{\boldsymbol{pixel}}\right]$$

SUMMARY:

VGA

$\boldsymbol{\varphi_{VGA,VERT} = 14.777[deg]}$
$\boldsymbol{\varphi_{VGA,HOR} = 19.619[deg]}$
$\boldsymbol{\varphi_{VGA,DIAG} = 24.391\,[deg]}$

$RESOLUTION_{VGA,VERT} \cong \mathbf{243.138}\left[\boldsymbol{m/_{pixel}}\right]$
$RESOLUTION_{VGA,HOR} \cong \mathbf{243.142}\left[\boldsymbol{m/_{pixel}}\right]$
$RESOLUTION_{VGA,DIAG} \cong \mathbf{243.141}\left[\boldsymbol{m/_{pixel}}\right]$

QVGA

$\boldsymbol{\varphi_{QVGA,VERT} = 12.004[deg]}$
$\boldsymbol{\varphi_{QVGA,HOR} = 15.960[deg]}$
$\boldsymbol{\varphi_{QVGA.DIAG} = 19.879\,[deg]}$

$RESOLUTION_{QVGA,VERT} \cong \mathbf{394.273}\left[\boldsymbol{m/_{pixel}}\right]$
$RESOLUTION_{QVGA,HOR} \cong \mathbf{394.270}\left[\boldsymbol{m/_{pixel}}\right]$
$RESOLUTION_{QVGA,DIAG} \cong \mathbf{394.286}\left[\boldsymbol{m/_{pixel}}\right]$

Date: April 4, 2016
Version: Version 1.01 (DRAFT)

Fox-1E

(RadFxSat 2)

System Requirements Specification

1 Introduction

This document specifies the system level requirements for the AMSAT Fox-1E satellite project. This 1-Unit CubeSat is one part of the AMSAT Fox program and includes a subset of the capabilities to be realized in the overall program.

Fox-1E is intended as a follow-on and upgrade to the initial Fox-1 series CubeSat satellites. The first four Fox-1 satellites flew single channel FM repeaters as their bus-supporting communications system. Fox-1E will have essentially the same configuration and basic bus structure as the earlier Fox-1 satellites, but with their single channel FM repeater transmitter and receiver replaced with a new wideband linear transponder. This type of amateur radio communications system will provide more channels for multiple, simultaneous radio contacts, as well as a higher data rate, continuous telemetry downlink.

In addition to its mission as a communications satellite, Fox-1E will host an experiment payload. The satellite will reserve mass and volume for the experiment and will provide DC power and communications capability to support experiment data downlinking. The experiment will be provided by students at Vanderbilt University's Institute for Space and Defense Electronics (ISDE).

1.1 Document History

DATE	VERSION	AUTHOR	SUMMARY
November 4, 2015	1.0	J. Buxton (N0JY)	Original Fox-1 SRS
April 4, 2016	1.01	E. Skoog (K1TVV)	Update draft for review/comment

1.2 Document Scope

The purpose of this document is to specify the requirements of the satellite at the system (i.e., "black box") level. It is intended to be used by hardware, software and mechanical designers to develop architecture/high-level design specifications. It is also intended to be used for test planning and development.

1.3 Document Format

This document provides requirements in numbered format. Each requirement is assigned a unique number. Additional information such as comments or examples provided for guidance or clarity is *italicized* to distinguish it from specific requirements.

1.4 References

1. AMSAT Fox-1 Concept of Operations, Version 1.03, October 19, 2011
2. CubeSat Design Specification, Rev. 13, February 20, 2014, The CubeSat Program Cal Poly SLO
3. Launch Services Program, Program Level Dispenser and CubeSat Requirements Document, LSP-REQ-317.01 Revision B, January 30, 2014, National Aeronautics and Space Administration (NASA)
4. ITU Radio Regulations, Edition of 2012, available from http://www.itu.int/publ/R-REG-RR-2012/en

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2 General Requirements

2.1 CubeSat Requirements

2.1.1 The satellite shall satisfy the requirements specified in the CubeSat Design Specification, Rev. 13.

2.1.2 The satellite shall satisfy the requirements specified in the NASA LSP-REQ-317.01 Revision B.

2.1.3 The satellite shall satisfy the requirements for a 1 Unit (single) CubeSat.

2.1.4 The satellite shall provide mass for an experiment payload up to 100 g.

2.1.5 The satellite shall provide volume for an experiment payload up to 95 x 95 x 31.4 mm. **<<equivalent to four (experiment slot) PCBs' volume, i.e., one VUC plus 3 REMs>>**

2.2 Environmental Requirements

2.2.1 The satellite avionics shall be designed for an operating temperature range of -40^0C to $+70^0$C.

2.2.2 The satellite shall be designed to operate in an approximate 500 to 700 km, sun-synchronous, circular orbit.

2.2.3 The satellite shall be designed to tolerate the radiation environment in orbit.

2.3 Reliability Requirements

2.3.1 The satellite shall be designed for a minimum 5-year, on-orbit lifetime.

2.4 Radio Frequency (RF) Regulatory Requirements

2.4.1 The satellite's RF transmitter shall meet or exceed the requirements specified in ITU Radio Regulations, Volume 1 Articles, Chapter 1 – Terminology and Technical Characteristics of Stations, Article 3.

2.4.2 All satellite uplinks shall be in the 2 meter band of the Amateur Satellite Service.

2.4.3 All satellite downlinks shall be in the 70 cm band of the Amateur Satellite Service.

2.4.4 All satellite transmitter and receiver generated frequencies shall deviate by no more than 5 parts-per-million from their specified values including initial accuracy and temperature variation.

2.4.5 All satellite frequencies shall be coordinated with the IARU.

2.4.6 The command uplink shall be a narrow band FM signal (+/- 5 kHz deviation) located outside of the user transponder passband.

The band plan with the actual coordinated frequencies will be specified in a separate document.

3 Functional Requirements

3.1 Antenna System

3.1.1 The satellite shall include a deployable antenna system.

3.2 Attitude Control

3.2.1 The satellite shall incorporate passive magnetic stabilization to align the deployed antennas with the magnetic field of the earth.

3.3 Access Ports

3.3.1 The satellite shall include a "Remove Before Flight" (RBF) pin as per the CubeSat Design Specification.

3.3.2 The satellite shall include an umbilical port as per the CubeSat Design Specification.

3.4 Pre-launch Features

3.4.1 The satellite battery and photovoltaic panels shall be electronically disconnected from the avionics when the "Remove Before Flight" pin is inserted, regardless of the state of the deployment switch(es).

3.4.2 The satellite shall provide a means to charge the battery via the umbilical port while integrated with the dispenser.

3.4.3 The satellite shall provide a means to run diagnostic tests via the umbilical port while integrated with the dispenser.

3.5 Power

3.5.1 The satellite shall produce electrical power from sunlight.

3.5.2 The satellite shall produce electrical power while in sunlight regardless of orientation and while tumbling or spinning.

3.5.3 The satellite shall produce sufficient average electrical power to operate continuously in the orbit of maximum eclipse.

3.5.4 The satellite shall provide sufficient battery capacity to operate continuously in the orbit of maximum eclipse.

3.5.5 The satellite shall not provide battery power to the main bus until approximately 90 seconds after activation of both deployment switches indicating successful launch vehicle dispenser separation.

<<Should McCann, Burns, et al provide additional (new) functional requirement statements, e.g., SSTV, Whole Orbit Data (WOD), etc.>>

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3.6 Experiment

3.6.1 The satellite shall provide DC power for an experiment payload.

3.6.2 The satellite shall provide a means to activate and deactivate the experiment payload.

3.6.3 The satellite shall provide a means to telemeter data from the experiment payload.

The experiment payload details will be specified in a separate document.

3.7 RF Uplink

3.7.1 The satellite shall include a linear uplink receiver.

3.7.2 The uplink receiver shall process signals in a linear manner. The receiver will process SSB, CW, PSK, and FSK signals to its intermediate frequency with intermodulation distortion (IMD) products no higher than -40 dBc when the maximum intended level signals are applied to the spacecraft.

3.8 RF Downlink

3.8.1 The satellite shall include a linear downlink transmitter.

3.8.2 The downlink transmitter shall be a linear transmitter with intermodulation products no higher than -20 dBc when the highest level output signal is at maximum output power.

3.9 Transponder

3.9.1 The satellite shall provide linear transponder operation via the RF uplink and RF downlink.

3.9.2 The user transponder shall have a -3dB bandwidth of 30 kHz and a -20dB bandwidth of 50 kHz, referenced to the center of the passband.

3.9.3 The transponder shall be an inverting transponder.

3.9.4 The transponder shall have a means of sensing and adjusting gain so that the highest level throughput signal is not distorted with intermodulation products higher than -20 dBc with multiple signals in the passband.

3.9.5 The transponder gain adjustment shall have a time constant of <TBD> seconds, so that the highest level signal in the passband will not 'pump' other signals in the passband by its modulation.

3.9.6 The transponder shall have a mechanism for detecting the level of signals in the uplink passband. This aggregate level shall have a threshold switching mechanism for activating and deactivating the satellite transmitter when no signals exceed the threshold. The transmitter shall be activated when the threshold is exceeded for at least two seconds.

The threshold mechanism shall continue to keep the transmitter activated for 30 seconds after the threshold conditions are no longer satisfied.

3.9.7 The transponder shall have a linear gain such that a received CW signal of <TBD> dBm will result in a power output of +23 dBm. Any other signals amplified in the passband shall create IMD products not to exceed -20 dBc in the passband of the transponder.

3.10 Telemetry Data

3.10.1 The satellite shall collect telemetry data.

3.10.2 The telemetry data shall include at a minimum, the measured parameters shown in Table 1.

Table 1

PARAMETER NAME	DESCRIPTION
CELL V	Voltages of battery cells
PANEL V	Voltages of solar panels
TOTAL I	Total DC current out of power system
PA I	DC current into RF power amp
BATTERY T	Temperature of battery
PANEL T	Temperatures of solar panels
TX T	Temperature of RF transmitter card
RX T	Temperature of RF receiver card

3.10.3 The measured parameters shall be sampled at least every 15 seconds.

3.10.4 The minimum and maximum values of each of the measured parameters shall be saved in non-volatile memory.

3.10.5 The telemetry data shall also include at a minimum, the calculated parameters shown in Table 2.

Table 2

PARAMETER NAME	DESCRIPTION
UP TIME	Total seconds since avionics power-up or the last Reset
SPIN	Satellite spin rate and direction

3.10.6 A telemetry frame shall include the current measured values, the saved minimum and maximum values, and the current calculated values.

The detailed telemetry interface will be specified in a separate document.

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3.11 Telemetry Transmission

3.11.1 The satellite shall send slow speed telemetry using BPSK on the RF downlink.

3.11.2 The downlink telemetry signal shall be a 1200 bps BPSK signal located outside the user transponder passband and shall be part of the frequency multiplexed downlink. The telemetry signal's peak power level shall be no greater than 40 dB below the maximum output power of the transponder.

3.11.3 Telemetry data shall be transmitted simultaneously with user transponder signals, and shall cease to be transmitted when the user transponder threshold signal "hang time' of 30 seconds has expired.

3.11.4 The telemetry transmission shall include telemetry frames.

3.11.5 The telemetry transmission shall also include experiment data.

3.12 Command Capability

3.12.1 The satellite shall provide a means to process commands sent via the RF uplink from authorized ground control stations.

3.12.2 The command receiver shall be on a frequency outside the transponder bandwidth.

3.12.3 A 1200 bps AFSK-FM via a NBFM channel demodulation capability shall be provided to the IHU for the purpose of transferring data and commands to the IHU. This AFSK-FM channel shall follow the FSK requirements of Bell 202 modems.

3.12.4 The uplink command receiver shall be capable of receiving and demodulating AFSK-FM signals at 1200 bps with an input signal level of 0.5 uV with a baseband Bit Error Rate (BER) of 1 x 10^{-4}.

3.12.5 The command uplink receiver will not be responsible for bit or byte synchronization, re-timing, or error correction.

3.12.6 The following commands shall be provided, as shown in Table 3, below.

Table 3

Command	Operation
SAFE MODE	Enter Safe Mode
INHIBIT TX	Inhibit RF transmission
ENABLE TX	Enable RF transmission
IHU OFF	Power off IHU
IHU ON	Power on IHU
CLEAR	Clear stored telemetry
TRANSPONDER MODE	Enter Transponder Mode
ENABLE AUTO-SAFE	Enable Auto-Safe Mode
DISABLE AUTO-SAFE	Disable Auto-Safe Mode

3.12.7 A SAFE MODE command shall cause the satellite to enter the Safe Mode.

3.12.8 An INHIBIT TX command shall disable the RF transmitter.

3.12.9 An ENABLE TX command shall enable the RF transmitter.

3.12.10 An IHU OFF command shall cause the IHU System to power off.

3.12.11 An IHU ON command shall cause the IHU System to power on.

3.12.12 A CLEAR command shall cause the satellite to clear the saved minimum and maximum telemetry parameter values.

3.12.13 A TRANSPONDER MODE command shall cause the satellite to enter the Transponder Mode.

3.12.14 An ENABLE AUTO-SAFE command shall enable the auto-safe mode state.

3.12.15 A DISABLE AUTO-SAFE command shall disable the auto-safe mode state.

The control interface details will be specified in a separate document.

3.13 On-Orbit Operating Modes

3.13.1 The satellite shall provide on-orbit operating modes as shown in Table 4.

Table 4

NAME	DESCRIPTION
Startup Mode	Wait 50 minutes and deploy antennas
Safe Mode	Wait 120 seconds then begin telemetry beacon sequencing; Experiment powered off
Auto-Safe Mode	If enabled, automatically detects a low battery condition and shuts down some major satellite activities
Transponder Mode	Linear transponder mode; telemetry channel and experiment active

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3.13.2 The satellite shall transition between its on-orbit operational modes as shown in the State Transition Diagram in Figure 1.

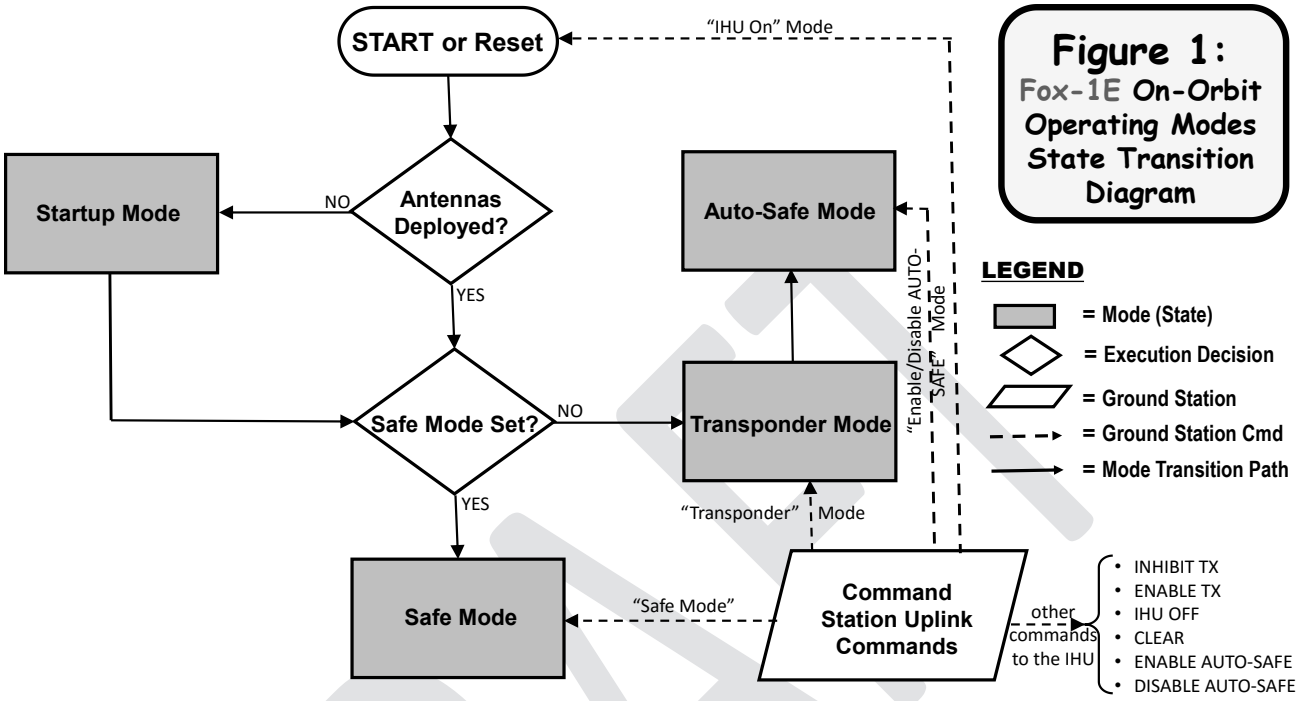

Figure 1: Fox-1E On-Orbit Operating Modes State Transition Diagram

3.13.3 Upon launch, a power cycle of the avionics, or after a reset action, the satellite shall enter the "START" point as shown in Figure 1.

3.13.4 An IHU ON command shall also cause the satellite to begin operation from the "START" point as shown in Figure 1.

3.13.5 If the antennas have not been deployed, the satellite shall enter Startup Mode.

3.13.5.1 In Startup Mode, the satellite shall wait at least 50 minutes before commanding antenna deployment and initiating RF transmissions.

3.13.5.2 After the antennas have been successfully deployed upon initial orbit, the satellite shall enter Safe Mode.

3.13.6 After a Reset action and antennas successfully deployed check, the satellite shall determine whether its last state was SAFE MODE.

3.13.6.1 If the last state was SAFE MODE. the satellite shall (re)enter SAFE MODE.

3.13.6.2 1200 bps BPSK telemetry beacon downlink channel operation shall occur during SAFE MODE. There shall be NO CW beacon functionality implemented in the satellite

3.13.6.3 If the last state was not SAFE MODE, the satellite shall enter TRANSPONDER MODE.

3.13.6.4 In TRANSPONDER MODE, the transponder and the telemetry shall be active.

3.13.7 The command RF uplink shall be monitored for commands in all modes.

3.14 Operational Timing Requirements

3.14.1 The satellite shall satisfy the operational times shown in Table 5.

Table 5

FUNCTION	TIME (± 5%)	OPERATIIONAL CONDITIONS
Burn Resistor Activation	≈ 4 seconds	Time allotted for the (activated) burn resistors' initial melting of the deployable antenna restrainers
Burn Resistors RE-activation	≈ 20 seconds	Time allotted for the (RE-activated) burn resistors' subsequent melting of the deployable antenna restrainers
Deployment Switch Notification Delay	≈ 90 seconds	Delay time from deployment switch physical activation to electronic activation report.
IHU Boot-Up/POST	< 20 seconds	Time for the Internal Housekeeping Unit (IHU) to boot-up and run Power On System Tests (POST)
Antenna/RF Initiation Delay	≈ 50 minutes	Antenna deployment and transmission inhibit time after dispenser launch
Beacon (Safe Mode) Duty Cycle	≈ 2 minutes	Elapsed time from end of beacon telemetry transmission to start of next beacon transmission while in SAFE MODE
Hang Timer	≈ 30 seconds	RF transmit carrier time after the uplink passband (aggregate) signal(s) no longer satisfy the threshold criteria.
Telemetry Period	≈ 15 seconds	Sampling period for all telemetry parameters
ENABLE TX Confirm	≈ 3 minutes	Time after receipt of ENABLE TX command before transmitting a telemetry beacon
Watchdog Timer	≈ 10 seconds	If IHU-directed tasks do not report back within this time period, the satellite will reset.

4 External Interface Documents

To fully specify the satellite's technical requirements, the following documents should be consulted:

1. IARU Coordinated Frequency Plan
2. Downlink Specification
3. Control Interface Specification
4. Experiment Payload Specification

5 Summary

The *Fox-1E* satellite will be AMSAT's first linear transponder CubeSat. Its primary mission is to provide linear transponder communications capability. The secondary mission is to host a university-provided experiment payload.

Date: Sept 26, 2016
Version: Version 1.00

AMSAT *Fox-1E*

Downlink Specification

1 Introduction

This document specifies downlink frame formats for the Fox-1E telemetry and experiment telemetry.

Document History

DATE	VERSION	SUMMARY
Sept 26, 2016	1.00	Initial Version

DATE	VERSION	SUMMARY

1.1 Document Scope

The purpose of this document is to specify the downlink protocol on the AMSAT Fox-1E spacecraft.

1.2 References

1. Fox1 Downlink Specification
2. Fox-1E System Requirements

1.3 Definitions

1.3.1 BPSK Downlink – Data transmitted at approximately 1200 bits per second on a separate carrier outside the transponder passband.

1.3.2 Spacecraft Telemetry – Downlink data containing specific information about spacecraft systems and health as defined in the System Requirements and related documents.

1.3.3 Experiment Telemetry – Downlink data containing specific information about the various experiment platforms flown on the satellite.

1.3.4 Frame – A set of data to be transmitted to the ground with a specific overall size comprised of a header, a sync vector, payloads and FEC check bytes.

1.3.5 Payload – A set of data with a specific overall size containing fields of a specific bit or byte length.

1.3.6 FEC – Forward Error Correction provided by the Reed-Solomon 225,223 encoding scheme.

2 Protocol Structure

2.1 Physical Layer

2.1.1 DBPSK Telemetry operation uses differential binary phase shift keying.

2.1.2 The details of the physical layer are shown in Table 1.

Table 1

Bit Rate	1200 bps
Spectral efficiency	1 bps/Hz
Modulation type	Differential Binary Phase Shift Keying (DBPSK)
Signal bandwidth	10 Hz to 2400 Hz (-3 dB points)
Spectral Mask	-20 dB at 2400 Hz
RF Channel Bandwidth	2400 Hz

2.2 Link Layer

2.2.1 The link layer protocol provides a 32 bit sync vector

2.2.2 Link layer shall include a header and a trailer surrounding the applications layer payloads to form data packets as shown in Table 2.

Table 2

Header	Applications Payloads	Trailer

2.2.3 The applications payload layer shall include satellite telemetry, experiment telemetry, and debug frames.

2.2.4 Debug frames may be used during ground testing but shall not be transmitted for flight

2.2.5 Bits shall be transmitted in the order of most significant bit first.

2.2.6 Bytes shall be transmitted in Little Endian order.

2.2.7 The link layer header structure shall be as shown in Table 3.

Table 3

Field	Size (Bits)	Type	Min Value	Max Value	Description
Fox ID	3	Unsigned	0x01	0x01	0x05 specifies Fox-1E (each Fox satellite will have a unique ID)
Reset Count	16	Unsigned	0x00	0xFFFF	Total number of times IHU has reset since initial on-orbit startup
Uptime	25	Unsigned	0x00	0x1FFFFFF	This is the IHU uptime in seconds since the last reset

2.2.7.1 Each link layer structure shall contain the payload types shown in table 4.

Table 4

Payload Type	Size (Bytes)	Description
1	58	Real-Time Telemetry Payload
2	58	Telemetry Maximum Values Payload
3	58	Telemetry Minimum Values Payload
4	232	4 Radiation Experiment Payloads (58 bytes each)

2.2.7.2 Reset Count and Uptime shall reflect the time at which the payload data was collected.

2.2.7.3 Reset Count and Uptime shall not be changed if the payload data has not been updated

2.2.7.4 Real-Time Telemetry Payload, Telemetry Maximum Values Payload, and Telemetry Minimum Values Payload data shall be padded with zeros to equal 58 bytes length for each.

2.2.8 Forward error correction (FEC) bytes shall be sent in the link layer trailer. The FEC shall be a Reed Solomon RS 255,223 code. (This provides 32 parity bytes per code word allowing error detection and correction capability.) Two code words will be required. 30 bytes of zero padding (which will not be transmitted) are added to the 416 bytes of header/payload data to equal the 446 bytes needed for 2 code words.

3 Link Layer Transmission Scheduling

3.1 Safe Mode Beacons

3.1.1 During Safe mode the telemetry will be sent in beacon mode, designed to conserve power. The transponder will be off and two frame will be sent every 2 minutes.

3.2 Transponder Mode

3.2.1 While the transponder is on telemetry will be sent continuously.

4 Application Layer Payload Data

4.1 Payload Type 0 – Debug Frame (NOT TO BE TRANSMITTED FOR FLIGHT)

Table 5

Field	Size (Bits)	Type	Min Value	Max Value	Description
UNDEFINED	1 - 464	Undefined	-	-	Debug data for ground testing

4.2 Payload Type 1 - Real-Time Telemetry Frame (Size = 429 bits)

Table 6

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
BATT A V	12	Unsigned	0x00	0xFFF	Battery pair A voltage raw value (0-2.5V scale)	0
BATT B V	12	Unsigned	0x00	0xFFF	Battery pairs A+B voltage raw value (0-3.3V scale)	12
BATT C V	12	Unsigned	0x00	0xFFF	Battery pairs A+B+C voltage raw value (0-5.0V scale) This value also represents the power bus voltage (VBATT)	24
BATT A T	12	Unsigned	0x00	0xFFF	Battery pair A temperature raw value	36
BATT B T	12	Unsigned	0x00	0xFFF	Battery pair B temperature raw value	48
BATT C T	12	Unsigned	0x00	0xFFF	Battery pair C temperature raw value	60
TOTAL BATT I	12	Signed	0x00	0xFFF	Total Battery DC current raw value	72
BATT Board Temperature	12	Unsigned	0x00	0xFFF	PC Board Temperature of BATT raw value	84
+X PANEL V	12	Unsigned	0x00	0xFFF	+X solar panel voltage raw value	96
-X PANEL V	12	Unsigned	0x00	0xFFF	-X solar panel voltage raw value	108
+Y PANEL V	12	Unsigned	0x00	0xFFF	+Y solar panel voltage raw value	120
-Y PANEL V	12	Unsigned	0x00	0xFFF	-Y solar panel voltage raw value	132
+Z PANEL V	12	Unsigned	0x00	0xFFF	+Z solar panel voltage raw value	144
-Z PANEL V	12	Unsigned	0x00	0xFFF	-Z solar panel voltage raw value	156
+X PANEL T	12	Unsigned	0x00	0xFFF	+X solar panel temperature raw value	168
-X PANEL T	12	Unsigned	0x00	0xFFF	-X solar panel temperature raw value	180
+Y PANEL T	12	Unsigned	0x00	0xFFF	+Y solar panel temperature raw value	192
-Y PANEL T	12	Unsigned	0x00	0xFFF	-Y solar panel temperature raw value	204
+Z PANEL T	12	Unsigned	0x00	0xFFF	+Z solar panel temperature raw value	216

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
-Z PANEL T	12	Unsigned	0x00	0xFFF	-Z solar panel temperature raw value	228
PSU Temperature	12	Unsigned	0x00	0xFFF	PSU card temperature raw value	240
SPIN	12	Signed	0x00	0xFFF	Calculated spin rate RPM using solar cells Bit 11 = sign Bits 10 to 8 = integer Bits 7 to 0 = fraction	252
TX PA Current	12	Unsigned	0x00	0xFFF	Transmit power amplifier current raw value	264
TX Temperature	12	Unsigned	0x00	0xFFF	Transmitter card temperature raw value	276
RX Temperature	12	Unsigned	0x00	0xFFF	Receiver card temperature raw value	288
RSSI	12	Unsigned	0x00	0xFFF	Received Signal Strength Indication raw value	300
IHU CPU Temperature	12	Unsigned	0x00	0xFFF	CPU Temperature of IHU raw value	312
Satellite X Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Raw Angle	324
Satellite Y Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Raw Angle	336
Satellite Z Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Raw Angle	348
EXP 4 Temperature	12	Unsigned	0x00	0xFFF	Experiment 4 card temperature raw value	360
PSU Current	12	Unsigned	0x00	0xFFF	PSU DC current	372
IHU Diagnostic Data	32	Unsigned	-	-	Diagnostic Data on IHU Performance	384
Experiment Failure Indication	4	Unsigned	0x00 0x08	0x01 0x09	Bit 0 is Experiment 1 Bit 1 is Experiment 2 (N/A on Fox-1A) Bit 2 is Experiment 3 (N/A on Fox-1A) Bit 3 is Experiment 4 State: 0 = Working, 1 = Failed	416

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
System I2C Failure Indications	3	Unsigned	0x00	0x07	Bit 0 is BATT Bit 1 is PSU Device 1 Bit 2 is PSU Device 2 State: 0 = Working, 1 = Failed	420
Number of Ground Commanded TLM Resets	4	Unsigned	0x00	0x0F	Number of times command stations reset stored telemetry	423
Antenna Deploy Sensors	2	Unsigned	0x00	0x03	Bit 0 is RCV Bit 1 is XMT State: 0 = stowed 1 = deployed	427

4.3 Payload Type 2 - Telemetry Maximum Values Frame (Size = 460 bits)

Table 7

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
BATT A V	12	Unsigned	0x00	0xFFF	Battery pair A high voltage raw value (0-2.5V scale)	0
BATT B V	12	Unsigned	0x00	0xFFF	Battery pairs A+B high voltage raw value (0-3.3V scale)	12
BATT C V	12	Unsigned	0x00	0xFFF	Battery pairs A+B+C high voltage raw value (0-5.0V scale) This value also represents the power bus voltage (VBATT)	24
BATT A T	12	Unsigned	0x00	0xFFF	Battery pair A high temperature raw value	36
BATT B T	12	Unsigned	0x00	0xFFF	Battery pair B high temperature raw value	48
BATT C T	12	Unsigned	0x00	0xFFF	Battery pair C high temperature raw value	60
TOTAL BATT I	12	Signed	0x00	0xFFF	Battery DC high current raw value	72
BATT Board Temperature	12	Unsigned	0x00	0xFFF	High PC Board Temperature of BATT raw value	84
+X PANEL V	12	Unsigned	0x00	0xFFF	+X solar panel high voltage raw value	96
-X PANEL V	12	Unsigned	0x00	0xFFF	-X solar panel high voltage raw value	108
+Y PANEL V	12	Unsigned	0x00	0xFFF	+Y solar panel high voltage raw value	120
-Y PANEL V	12	Unsigned	0x00	0xFFF	-Y solar panel high voltage raw value	132
+Z PANEL V	12	Unsigned	0x00	0xFFF	+Z solar panel high voltage raw value	144
-Z PANEL V	12	Unsigned	0x00	0xFFF	-Z solar panel high voltage raw value	156
+X PANEL T	12	Unsigned	0x00	0xFFF	+X solar panel high temperature raw value	168

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
-X PANEL T	12	Unsigned	0x00	0xFFF	-X solar panel high temperature raw value	180
+Y PANEL T	12	Unsigned	0x00	0xFFF	+Y solar panel high temperature raw value	192
-Y PANEL T	12	Unsigned	0x00	0xFFF	-Y solar panel high temperature raw value	204
+Z PANEL T	12	Unsigned	0x00	0xFFF	+Z solar panel high temperature raw value	216
-Z PANEL T	12	Unsigned	0x00	0xFFF	-Z solar panel high temperature raw value	228
PSU Temperature	12	Unsigned	0x00	0xFFF	PSU card high temperature raw value	240
SPIN	12	Signed	0x00	0xFFF	Highest calculated spin rate RPM using solar cells	252
TX PA Current	12	Unsigned	0x00	0xFFF	Transmit power amplifier high current raw value	264
TX Temperature	12	Unsigned	0x00	0xFFF	Transmitter card high temperature raw value	276
RX Temperature	12	Unsigned	0x00	0xFFF	Receiver card high temperature raw value	288
RSSI	12	Unsigned	0x00	0xFFF	High Received Signal Strength Indication raw value	300
IHU CPU Temperature	12	Unsigned	0x00	0xFFF	High CPU Temperature of IHU raw value	312
Satellite X Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Highest Raw Angle	324
Satellite Y Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Highest Raw Angle	336
Satellite Z Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Highest Raw Angle	348

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
EXP 4 Temperature	12	Unsigned	0x00	0xFFF	Experiment 4 card high temperature raw value	360
PSU Current	12	Unsigned	0x00	0xFFF	PSU DC high current	372
IHU Hard Error Data	32	Unsigned	-	-	Diagnostic Data on IHU Hard Errors	384
MAX Timestamp Reset Count	16	Unsigned	0x00	0xFFFF	At last MAX, total number of times IHU has reset since initial on-orbit startup	416
MAX Timestamp Uptime	25	Unsigned	0x00	0x1FFFFFF	At last MAX, the IHU uptime in seconds since the last reset	432
Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode Active	457
Auto-Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode activated by Auto-Safe	458
Auto-Safe Enabled	1	Unsigned	0x00	0x01	State: 1 = Auto-Safe Mode enabled	459

4.4 Payload Type 3 - Telemetry Minimum Values Frame (Size = 460 bits)

Table 8

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
BATT A V	12	Unsigned	0x00	0xFFF	Battery pair A low voltage raw value (0-2.5V scale)	0
BATT B V	12	Unsigned	0x00	0xFFF	Battery pair A+B low voltage raw value (0-3.3V scale)	12
BATT C V	12	Unsigned	0x00	0xFFF	Battery pair A+B+C low voltage raw value (0-5.0V scale) This value also represents the power bus voltage (VBATT)	24
BATT A T	12	Unsigned	0x00	0xFFF	Battery pair A low temperature raw value	36
BATT B T	12	Unsigned	0x00	0xFFF	Battery pair B low temperature raw value	48
BATT C T	12	Unsigned	0x00	0xFFF	Battery pair C low temperature raw value	60
TOTAL BATT I	12	Signed	0x00	0xFFF	Battery DC low current raw value	72
BATT Board Temperature	12	Unsigned	0x00	0xFFF	Low PC Board Temperature of BATT raw value	84
+X PANEL V	12	Unsigned	0x00	0xFFF	+X solar panel low voltage raw value	96
-X PANEL V	12	Unsigned	0x00	0xFFF	-X solar panel low voltage raw value	108
+Y PANEL V	12	Unsigned	0x00	0xFFF	+Y solar panel low voltage raw value	120
-Y PANEL V	12	Unsigned	0x00	0xFFF	-Y solar panel low voltage raw value	132
+Z PANEL V	12	Unsigned	0x00	0xFFF	+Z solar panel low voltage raw value	144
-Z PANEL V	12	Unsigned	0x00	0xFFF	-Z solar panel low voltage raw value	156
+X PANEL T	12	Unsigned	0x00	0xFFF	+X solar panel low temperature raw value	168

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
-X PANEL T	12	Unsigned	0x00	0xFFF	-X solar panel low temperature raw value	180
+Y PANEL T	12	Unsigned	0x00	0xFFF	+Y solar panel low temperature raw value	192
-Y PANEL T	12	Unsigned	0x00	0xFFF	-Y solar panel low temperature raw value	204
+Z PANEL T	12	Unsigned	0x00	0xFFF	+Z solar panel low temperature raw value	216
-Z PANEL T	12	Unsigned	0x00	0xFFF	-Z solar panel low temperature raw value	228
PSU Temperature	12	Unsigned	0x00	0xFFF	PSU card low temperature raw value	240
SPIN	12	Signed	0x00	0xFFF	Lowest calculated spin rate RPM using solar cells	252
TX PA Current	12	Unsigned	0x00	0xFFF	Transmit power amplifier low current raw value	264
TX Temperature	12	Unsigned	0x00	0xFFF	Transmitter card low temperature raw value	276
RX Temperature	12	Unsigned	0x00	0xFFF	Receiver card low temperature raw value	288
RSSI	12	Unsigned	0x00	0xFFF	Low Received Signal Strength Indication raw value	300
IHU CPU Temperature	12	Unsigned	0x00	0xFFF	Low CPU Temperature of IHU raw value	312
Satellite X Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Lowest Raw Angle	324
Satellite Y Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Lowest Raw Angle	336
Satellite Z Axis Angular Velocity	12	Unsigned	0x00	0xFFF	Lowest Raw Angle	348

Field	Size (Bits)	Type	Min Value	Max Value	Description	Bit Offset
EXP 4 Temperature	12	Unsigned	0x00	0xFFF	Experiment 4 card low temperature raw value	360
PSU Current	12	Unsigned	0x00	0xFFF	PSU DC low current	372
IHU Soft Error Data	32	Unsigned	-	-	Diagnostic Data on IHU Soft Errors	384
MIN Timestamp Reset Count	16	Unsigned	0x00	0xFFFF	At last MIN, total number of times IHU has reset since initial on-orbit startup	416
MIN Timestamp Uptime	25	Unsigned	0x00	0x1FFFFFF	At last MIN, the IHU uptime in seconds since the last reset	432
Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode Active	457
Auto-Safe Mode Indication	1	Unsigned	0x00	0x01	State: 1 = Safe Mode activated by Auto-Safe	458
Auto-Safe Enabled	1	Unsigned	0x00	0x01	State: 1 = Auto-Safe Mode enabled	459

4.5 Payload Type 4 - Radiation Experiment Data Frame (Size = 464 bits)

Table 9

Field	Size (Bytes)	Type	Min Value	Max Value	Description
Data	58	Unsigned	-	-	Experiment 1 Data

The following boards will be in the experiment slots:

- 1 VUC experiment controller board interfacing with AMSAT Fox-1 satellite bus in Position 1 (EXP1)
- 1 LEP in Position 2 (EXP2) (as flown on Fox-1A),
- 1 LEPF in Position 3 (EXP3) (new),
- 1 REM in Position 4 (EXP4) (as flown on Fox-1B)

The VUC will send the 58 byte chunks as per the ICD. This will contain a set of Telemetry data for the experiments that the VUC is controlling.

Id	FIELD	BITS	UNIT	CONVERSION	SHORT_NAME	DESCRIPTION
0	VUC_STATE	4	NONE	27	Status	Status of the Vanderbilt University Controller
1	VUC_RESTARTS	8	NONE	1	Restarts	Number of restarts by the Vanderbilt University Controller
2	VUC_UPTIME	20	s	25	Uptime	Uptime of the Vanderbilt University Controller
3	State1	4	NONE	27	State	Vulcan Experiment 1 State
4	State2	4	NONE	27	State	Vulcan Experiment 2 State
5	State3	4	NONE	27	State	Vulcan Experiment 3 State
6	State4	4	NONE	27	State	Vulcan Experiment 4 State
7	Power1	8	mW	0	Power	Vulcan Experiment 1 Power
8	Power2	8	mW	0	Power	Vulcan Experiment 2 Power
9	Power3	8	mW	0	Power	Vulcan Experiment 3 Power
10	Power4	8	mW	0	Power	Vulcan Experiment 4 Power
11	REM1	80	NONE	0	NONE	NONE
12	REM2_RESETS	8	NONE	1	Resets	Number of times the REM2 Experiment has reset
13	REM2_UPTIME	16	s	25	Uptime	Uptime of the REM2 Experiment
14	REM2_CORE_VOLTAGE	8	mV	25	Core Voltage	REM2 Core Voltage
15	REM2_SEU_LIVETIME	32	s	1	SEU Livetime	REM2 SEU Livetime
16	REM2_UPSETS	16	NONE	1	Memory	Cumulative number of

					Errors	memory upsets in REM2 Experiment
17	REM3_RESETS	8	NONE	1	Resets	Number of times the REM3 Experiment has reset
18	REM3_UPTIME	16	s	25	Uptime	Uptime of the REM3 Experiment
19	REM3_CORE_VOLTAGE	8	mV	25	Core Voltage	REM3 Core Voltage
20	REM3_SEU_LIVETIME	32	s	1	SEU Livetime	REM3 SEU Livetime
21	REM3_UPSETS	16	NONE	1	Memory Errors	Cumulative number of memory upsets in REM3 Experiment
22	REM4_RESETS	8	NONE	1	Resets	Number of times the REM4 Experiment has reset
23	REM4_UPTIME	16	s	25	Uptime	Uptime of the REM4 Experiment
24	REM4_CORE_VOLTAGE	8	mV	25	Core Voltage	REM4 Core Voltage
25	REM4_SEU_LIVETIME	32	s	1	SEU Livetime	REM4 SEU Livetime
26	REM4_UPSETS	16	NONE	1	Memory Errors	Cumulative number of memory upsets in REM4 Experiment

Fox 1-E Linear Transponder Average Power Tracking

Marc Franco, N2UO – Dan Habecker, W9EQ

May 2016

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Fox 1-E is the first satellite of the Fox series to feature a linear transponder. The downlink will be on the 70 cm band. The preliminary design goals are as follows:

Frequency: 435.8 MHz (nominal).

Bandwidth: 30 KHz.

Output power: 250 mW.

IMD: -20 dBc.

Harmonics: meet FCC.

Supply voltage: satellite battery, nominal 3.6 V.

We have chosen the RFPA0133 integrated circuit made by Qorvo (formerly RFMD) using their GaAs HBT process. This power amplifier provides more than 30 dB of gain. The output match is external, allowing for the use of low loss components. The power added efficiency of the PA is greater than 60%.

Linear transponders can be reasonably efficient when operated as close to saturation as possible while maintaining the required linearity. However, when relaying weak signals or the satellite's beacon, their efficiency will be severely degraded. This is true for any linear amplifier; since the load resistance RL is related to the supply voltage Vcc and the output power Po by the following equation,

$$RL = \frac{Vcc^2}{2Po}$$

any decrease in output power will result in a load resistance that is higher than that for maximum power, where the amplifier operates efficiently. One approach to maintain the efficiency high is to adjust the Vcc according to the output power in order to maintain RL constant. This will minimize the amount of energy wasted in heat. Three methods to control the Vcc are shown in Fig. 1: fixed Vcc, envelope tracking, and average power tracking.

In the fixed Vcc case, the amount of wasted energy is very large. No matter what the output power is, the Vcc is adjusted to provide the maximum peak power, and it is not varied when the power is lowered. Envelope tracking (ET), on the other hand, does exactly the opposite: it adjusts the Vcc following the envelope of the signal, so the Vcc value is optimum at all times. This is similar to the HELAPS or Envelope Elimination and Restoration methods used in past satellites. The advantage of ET over EER is that it is simpler to implement and it is easier to achieve good linearity. However, it takes a significant amount of energy to implement ET; there is a minimum amount of current that needs to be drawn, no matter what the power amplifier power is, for the envelope processing. In the case of a large amplifier, let's say, above 5 W, the current needed to implement ET is negligible, but at much lower RF power levels, the complexity and current needed are hard to justify.

Another way to improve the efficiency of a power amplifier when operated at a significant back off level is to use Average Power Tracking (APT). In this case, the value of the Vcc does not follow the instantaneous amplitude of the envelope, but it follows its average value. The complexity required in the modulator is a fraction of what is needed for ET, since now the Vcc envelope frequency is much lower. Although the efficiency achieved with this method is not as high as with ET, it is very convenient for small power amplifiers since the overhead current needed is much lower than with ET.

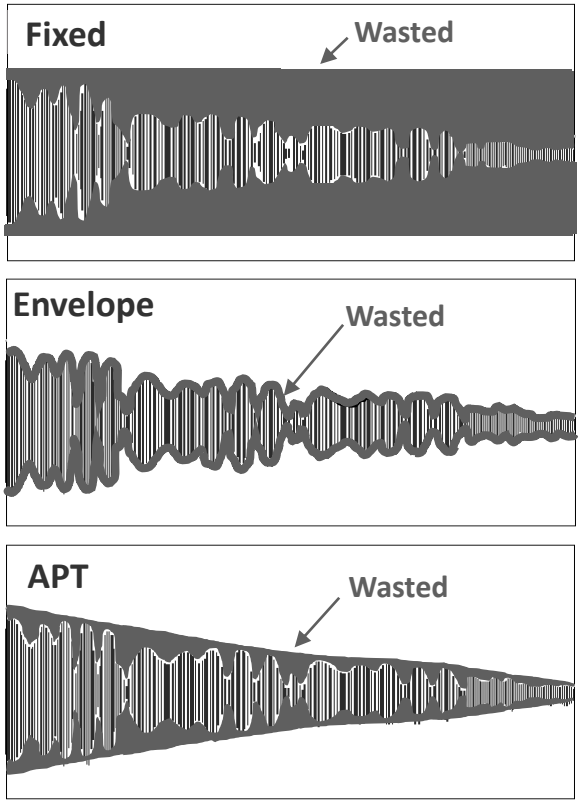


Fig. 1 – Time domain waveforms showing wasted power in fixed Vcc, average power tracking and envelope tracking

In APT, the output of the power amplifier is sampled and applied to a peak power detector. The output of the detector drives a high efficiency dc to dc converter that reduces the Vcc applied to the PA directly proportionally to the time average of the peak output power. Ideally, the peak detector should be placed at the input of the amplifier, but since the gain of this PA is not affected significantly by the change in Vcc value, the detector can be placed at the output without causing any instability.

Fig. 2 shows the schematic diagram of a practical implementation of the APT method. The detector is a Linear Technology LTC5533, and the dc to dc converter is a Linear Technology LTC1772. The Vcc of both stages in the RFPA0133 is controlled by the dc to dc converter.

The peak/hold function is implemented by adding some capacitance to ground after diode D1 (not shown in the schematic). The time constant should be found experimentally using real SSB and CW signals in the passband, but we have determined that between 1 to 2 seconds is satisfactory.

The current savings of the APT method can be seen in Fig. 3. Here, the current drawn by the amplifier is plotted both with the APT system on or by simply applying a fixed Vcc to the amplifier. The difference is quite significant at low power levels. In fact, if the satellite is to transmit only the beacon, the current needed will be minimized. Implementing a “squelch” type circuit for weak SSB and CW signals is not straightforward, as it is on FM.

The peak power detector used for the APT control can also be used for telemetry and to implement an automatic gain control in the transponder. The total current drawn by the amplifier biasing and power control circuit is 14 mA at 2.9 V.

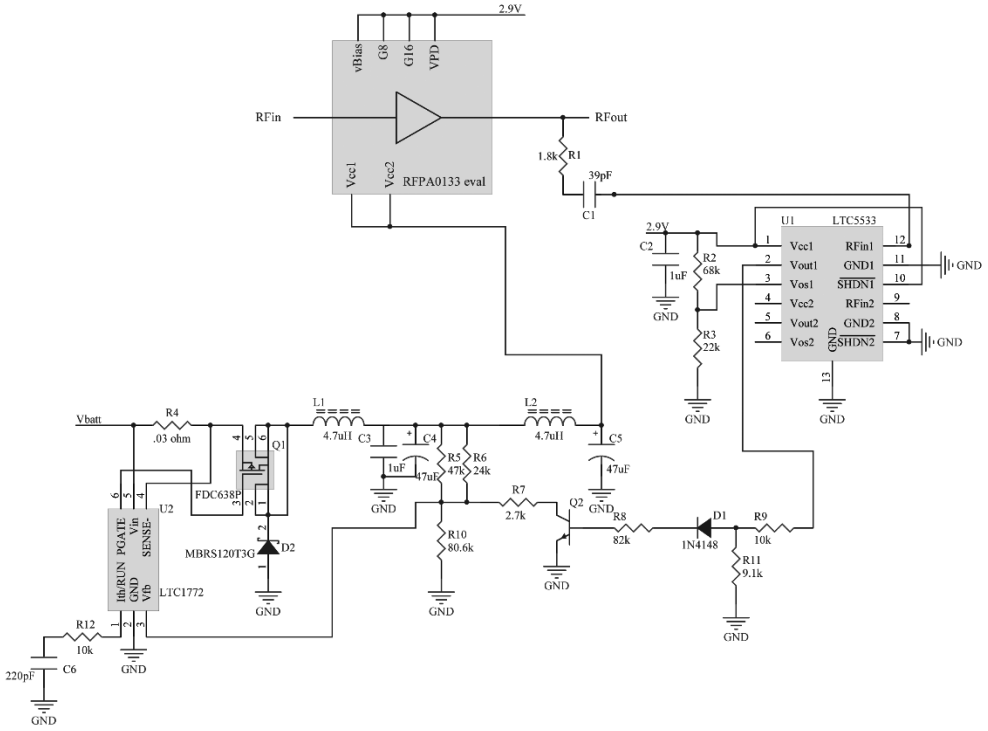


Fig. 2 – Schematic of the Average Power Tracking

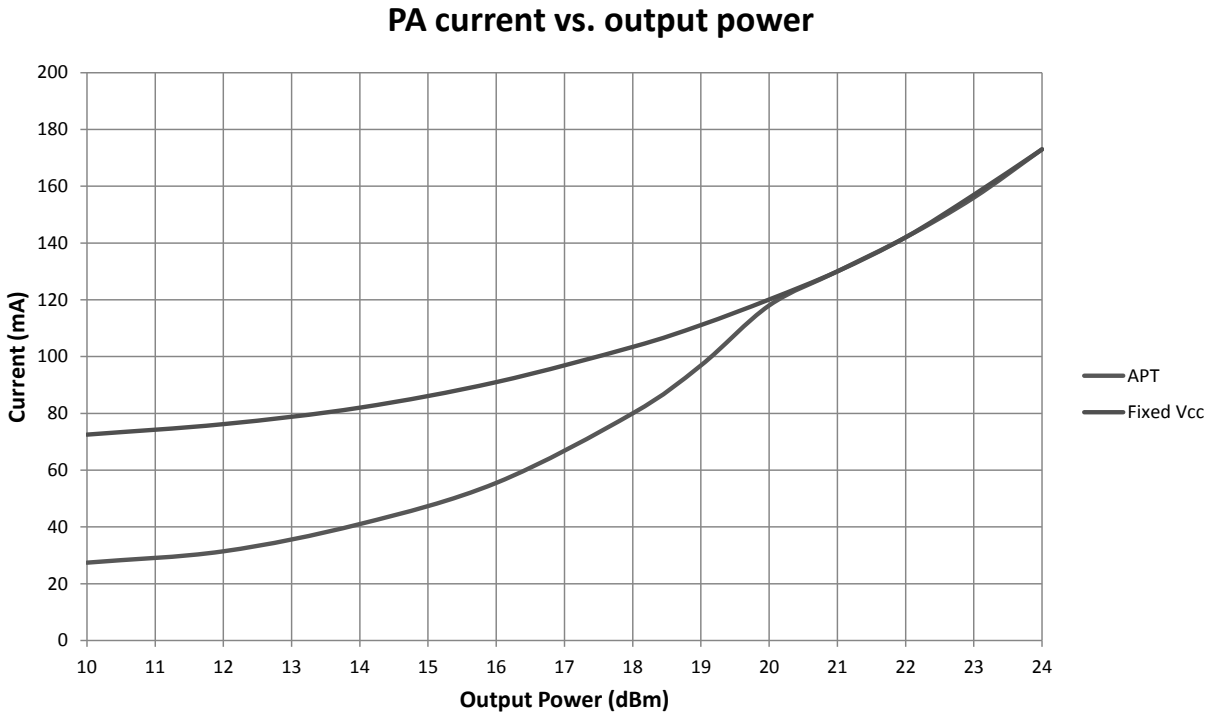


Fig. 3 – Measured current draw of the power amplifier using APT or a fixed Vcc

The linearity of the amplifier is maintained at all voltages. As an example, the measured two-tone spectrum at 10 dBm average power is shown in Fig. 4, whereas the two-tone spectrum at 23.7 dBm is shown in Fig. 5. Fig. 6 shows the 12-tone spectrum at 21.8 dBm total average power.

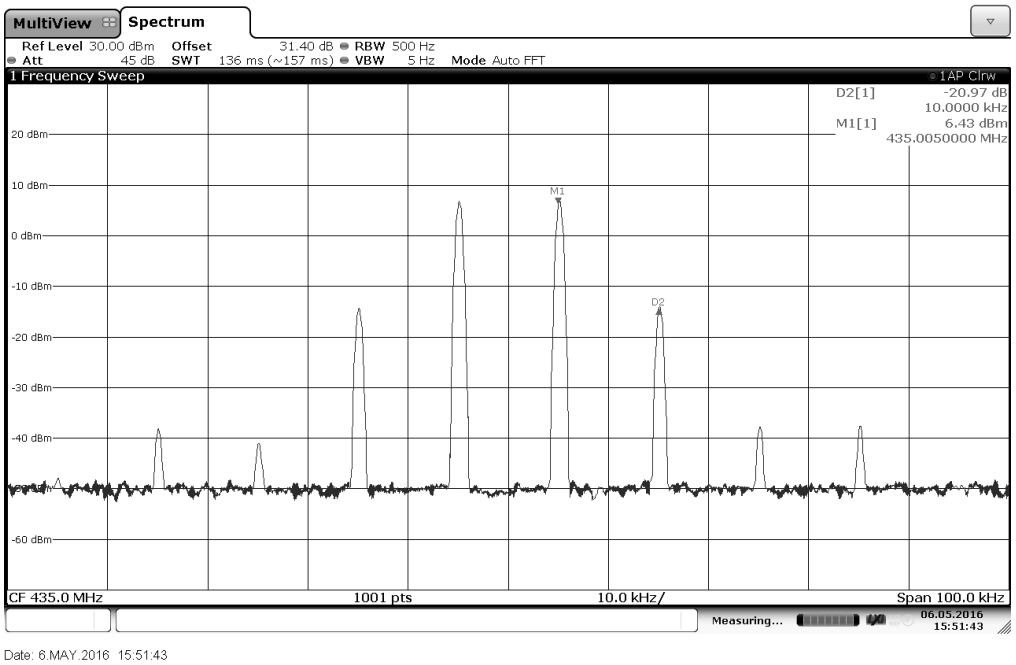


Fig. 4 – Measured two-tone spectrum at 21.8 dBm using APT

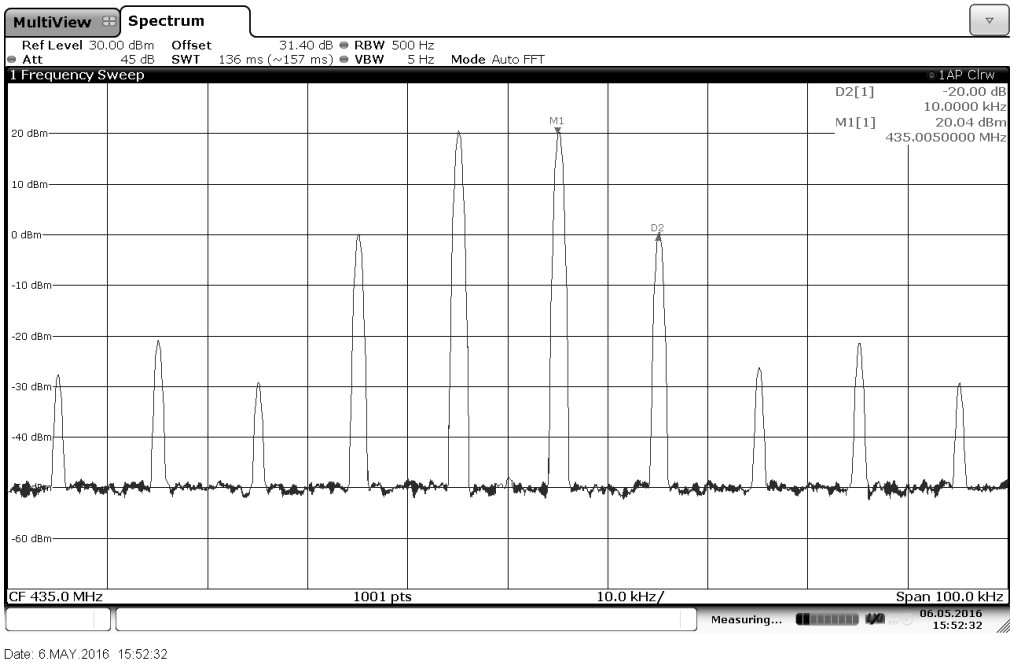


Fig. 5 – Measured two-tone spectrum at 23.7 dBm using APT

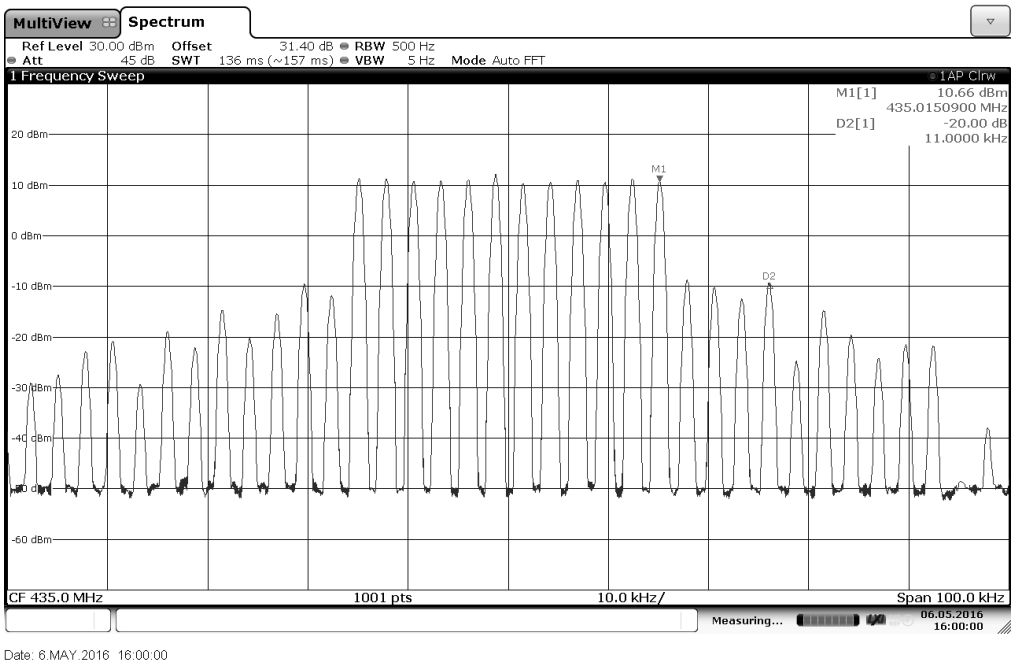
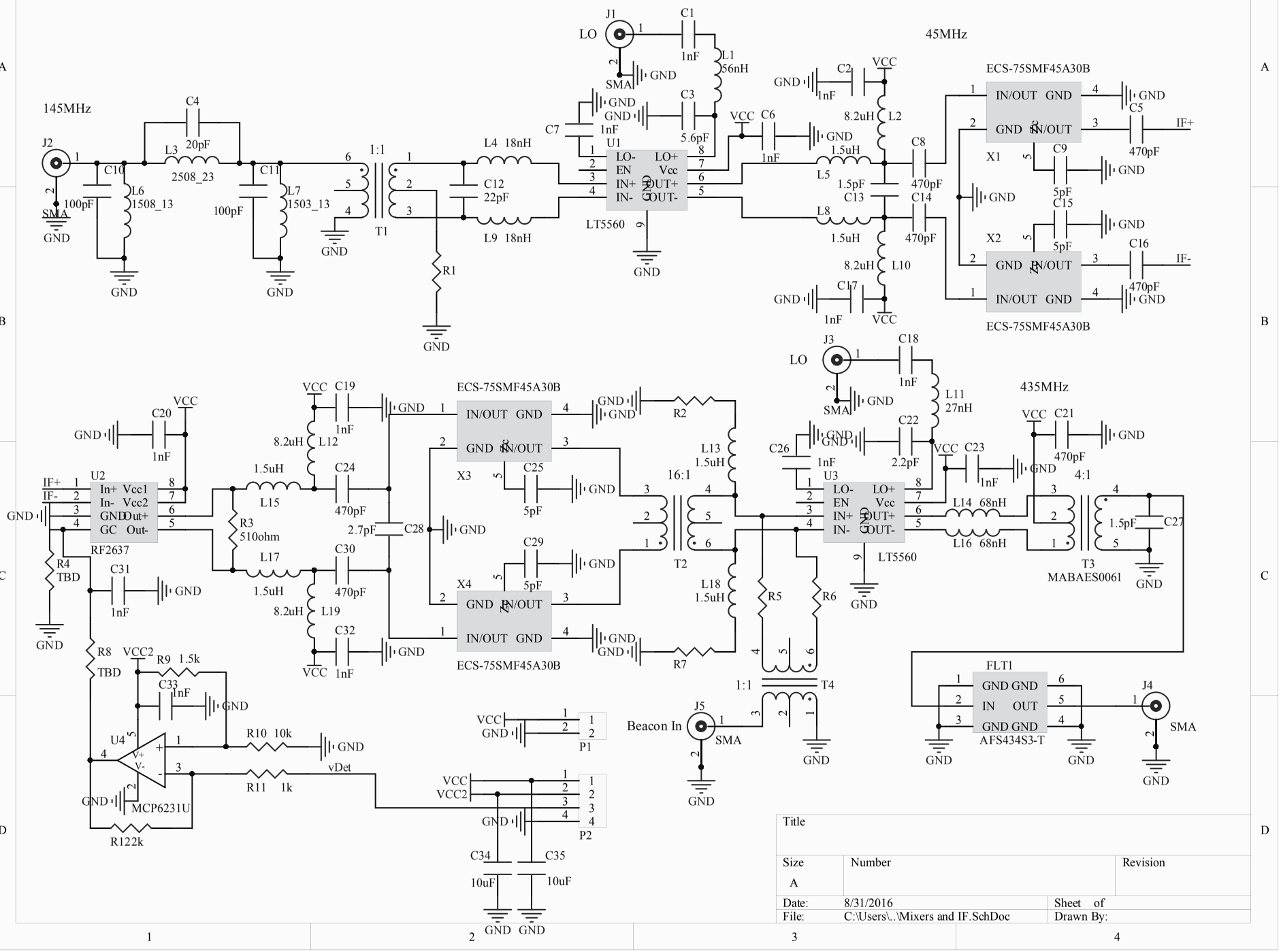


Fig. 6 – Measured twelve-tone spectrum spread out 30 KHz at 21.8 dBm using APT


145MHz
45MHz
435MHz
LO
SMA
GND
VCC
VCC2
J1
J2
J3
J4
J5
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
C11
C12
C13
C14
C15
C16
C17
C18
C19
C20
C21
C22
C23
C24
C25
C26
C27
C28
C29
C30
C31
C32
C33
C34
C35
1nF
2.2pF
5.6pF
100pF
22pF
470pF
5pF
L1
56nH
L2
8.2uH
L3
20pF
2508_23
L4
18nH
L5
1.5uH
L6
1508_13
L7
1503_13
L8
L9
18nH
L10
L11
27nH
L12
L13
L14
68nH
L15
L16
68nH
L17
L18
L19
1.5uH
1.5pF
2.7pF
T1
1:1
T2
16:1
T3
MABAES0061
4:1
T4
R1
R2
R3
510ohm
R4
TBD
R5
R6
R7
R8
TBD
R9
1.5k
R10
10k
R11
1k
R122k
vDet
U1
LT5560
LO-
LO+
EN
Vcc
IN+
OUT+
IN-
OUT-
U2
RF2637
IF+
IF-
In+
Vcc1
In-
Vcc2
GND
Out+
GC
Out-
U3
U4
MCP6231U
V+
V-
ECS-75SMF45A30B
IN/OUT
X1
X2
X3
X4
IF+
IF-
FLT1
AFS434S3-T
Beacon In
P1
P2
10uF
Title
Size
A
Number
Revision
Date:
8/31/2016
Sheet of
File:
C:\Users\..\Mixers and IF.SchDoc
Drawn By:

FOX1E 1200 BPS BPSK modulator

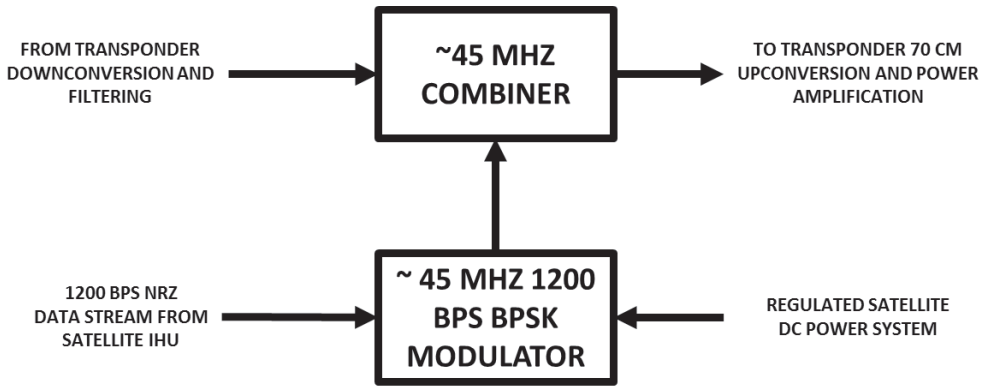
John Klingelhoeffer, WB4LNM

Current revision: 27 August 2016

Introduction: The AMSAT FOX1E has been discussed as providing a 1200 BPS BPSK downlink telemetry channel with a carrier outside of the user transponder bandwidth. This would increase the bandwidth of the telemetry downlink bandwidth compared with FOX1A-D, providing for a higher speed continuous scientific data downlink, and making the satellite compatible with legacy AMSAT telemetry downlink ground stations.

Discussion of the generation of this signal has previously been mentioned both as firmware-based in the IHU and hardware-based in the transponder transmitter. This document will address the later generation method *only*. This document proposes an approach to generate BPSK that requires significantly less system power, which is critical on small satellites. This is a concept document and is not a detailed design which is left to the AMSAT volunteer.

Requirements: The FOX1E transponder requires an approximately 45 MHz, low level, 1200 BPS BPSK signal that can be combined into the transponder after user bandwidth filtering and prior to up-conversion to 70 cm.


FROM TRANSPONDER DOWNCONVERSION AND FILTERING
~45 MHZ COMBINER
TO TRANSPONDER 70 CM UPCONVERSION AND POWER AMPLIFICATION
1200 BPS NRZ DATA STREAM FROM SATELLITE IHU
~ 45 MHZ 1200 BPS BPSK MODULATOR
REGULATED SATELLITE DC POWER SYSTEM

This document contains Technical Data whose export is restricted by the Arms Export Control Act (Title 22, U.S.C., Sec 2751, et seq.). Violations of these export laws are subject to severe criminal penalties.

Approach: The hardware modulator subsystem proposed consists of two main blocks, a carrier generator and the BPSK modulator itself.

The carrier generator would be a conventional, third-overtone, Colpitts crystal oscillator. The oscillator may or may not be temperature-compensated depending upon the desire to stabilize the frequency over long periods of time. In the short term, after mixing with the up-converter local oscillator and amplified, this signals frequency drift will be overwhelmingly dominated by short-term Doppler shift which will be many orders of magnitude more than the long-term temperature-induced drift. The continuous carrier wave output of this oscillator is at a frequency close to the 45 MHz center frequency of the linear transponder IF, but outside the user passband.

The second block of the BPSK function is the modulator itself. What is proposed herein is to use a quadruple analog switch instead of the more traditional double balanced mixer. This minimizes the interfacing drive needs from the NRZ data stream control input and therefore power. It allows the BPSK stream to be generated with much lower power levels than traditional methods.

Quad bilateral analog switches (QBS) have progressed in performance significantly since the days of the original CD4066, which was only functional to several megahertz at best. In this instance, the switch proposed for this application is the Texas Instruments TS112A44513DR:

http://www.ti.com/lit/ds/symlink/ts12a44514.pdf.

This IC has a 530 MHz high frequency cutoff at 5V operation, although it is operable down to 2.7 Volts. There may be better quad analog switches available for this specific application – no extensive survey was made. A more comprehensive search by the AMSAT detail designer is recommended during detail design.

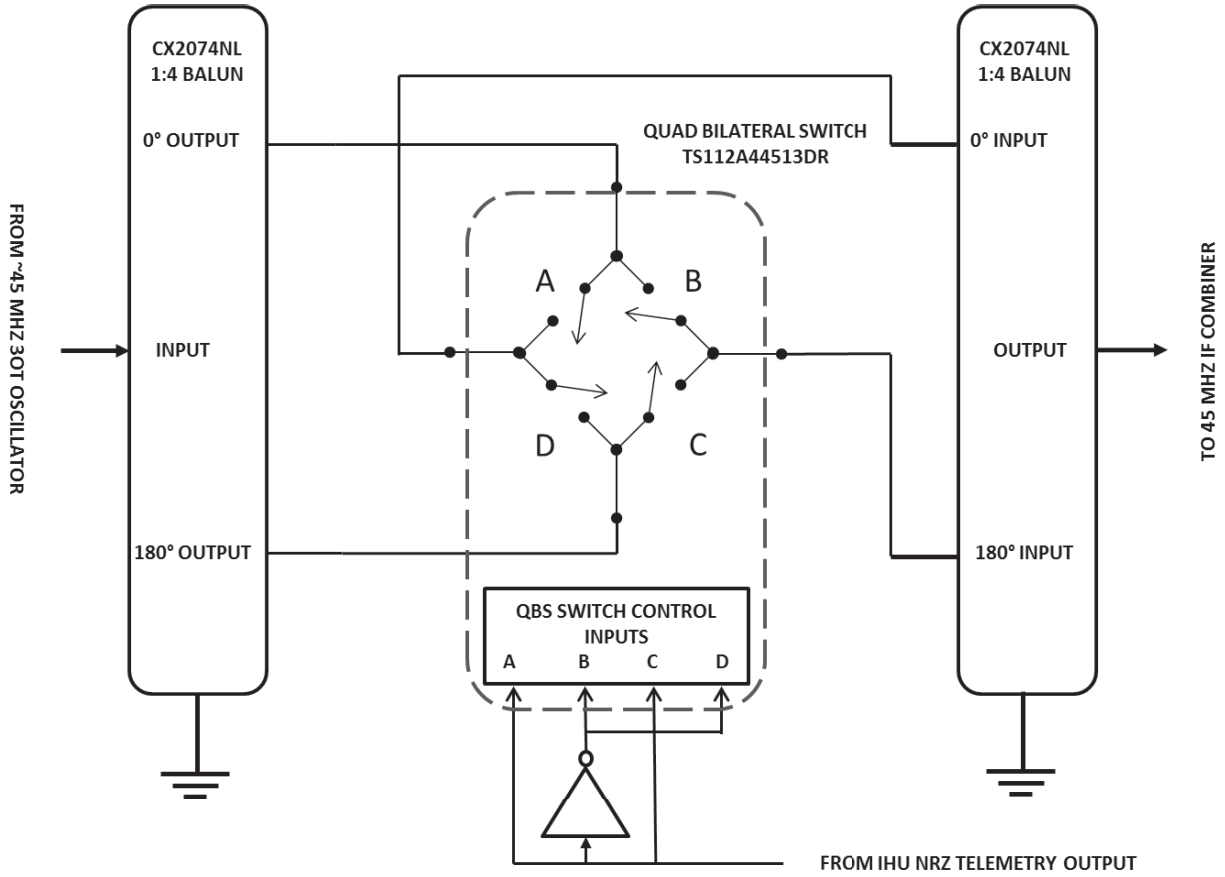
The input and output signal processing to the quad bilateral analog switch by baluns allows the ~45 MHz signal to be split and combined in-phase and out of

phase 180 degrees. One such balun is the Pulse Electronics CX2074NL unit, although as with the QBS, other devices are available.

http://www.digikey.com/product-detail/en/pulse-electronics-corporation/CX2074NL/553-1655-ND/2265447

This combination of parts is shown in the block diagrams on the following pages to help visualize the action of the modulator. For this discussion, the four switches of the QBS are designated as switches A,B,C and D.

The control signal for the QBS is the 1200 BPS NRZ telemetry output stream of the IHU. This is a CMOS level digital signal. The non-inverted version of the control signal comes directly from the IHU, while an inverted version of the same signal is produced by the inverter shown in the diagram. The inverted and not-inverted signals each control two of the switches at a time, leaving the other two in the opposite state.



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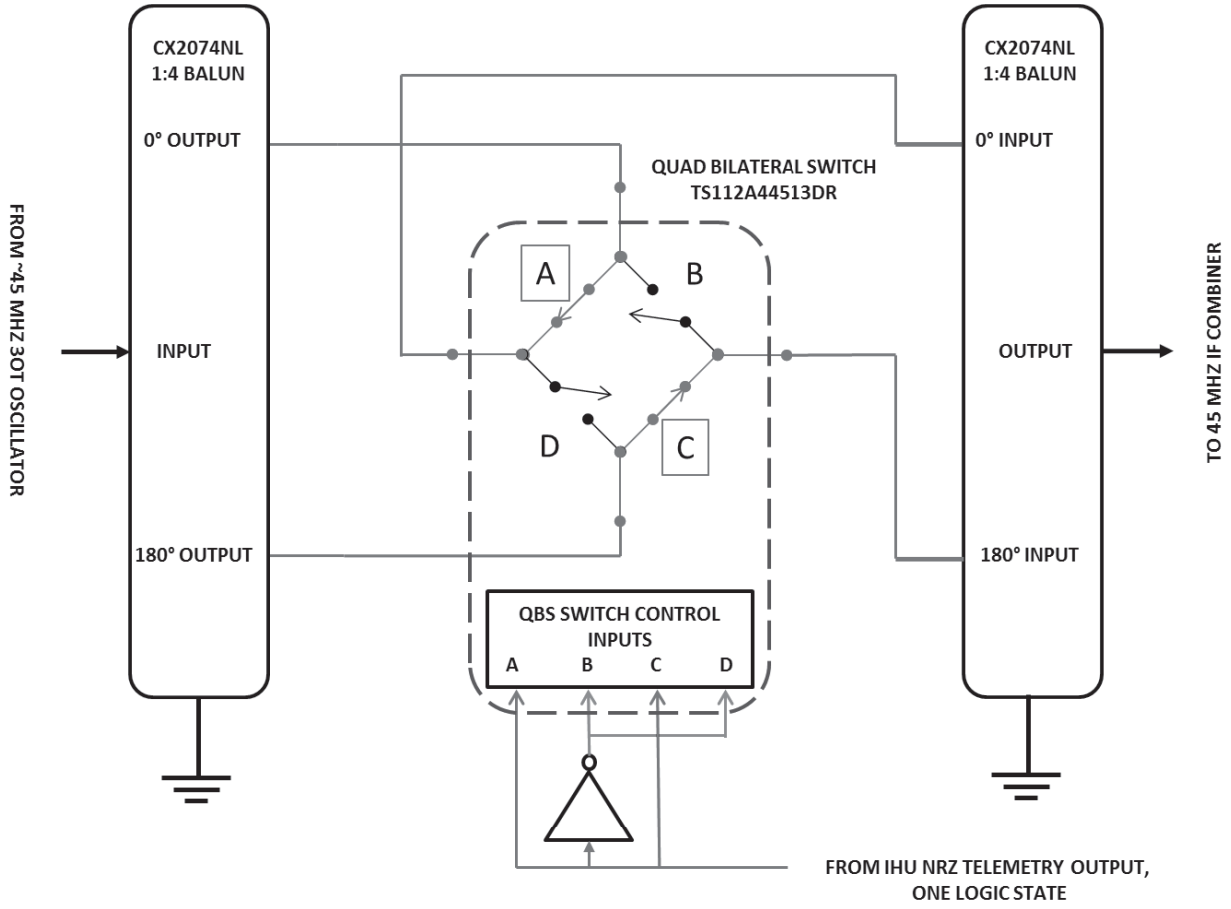
In the diagram shown, there are two states for the QBS IC; one is with the NRZ input signal in the logic zero state and one for the logic one state. In one state, switches A and C will be closed and B and D open, and in the other state A and C will be open and B and D will be closed.

As a visual aid, if the telemetry NRZ output of the IHU is in the "one" state, logic high, switches A and C close and B and D remain open:



This allows the zero phase output pin of the input balun to be connected to the zero degree phase input pin on the output balun via switch A. Simultaneously, it connects the 180 degree output pin of the input balun to be connected to the 180 degree input pin on the output balun. In this state, the output RF carrier is in phase with the input RF carrier.

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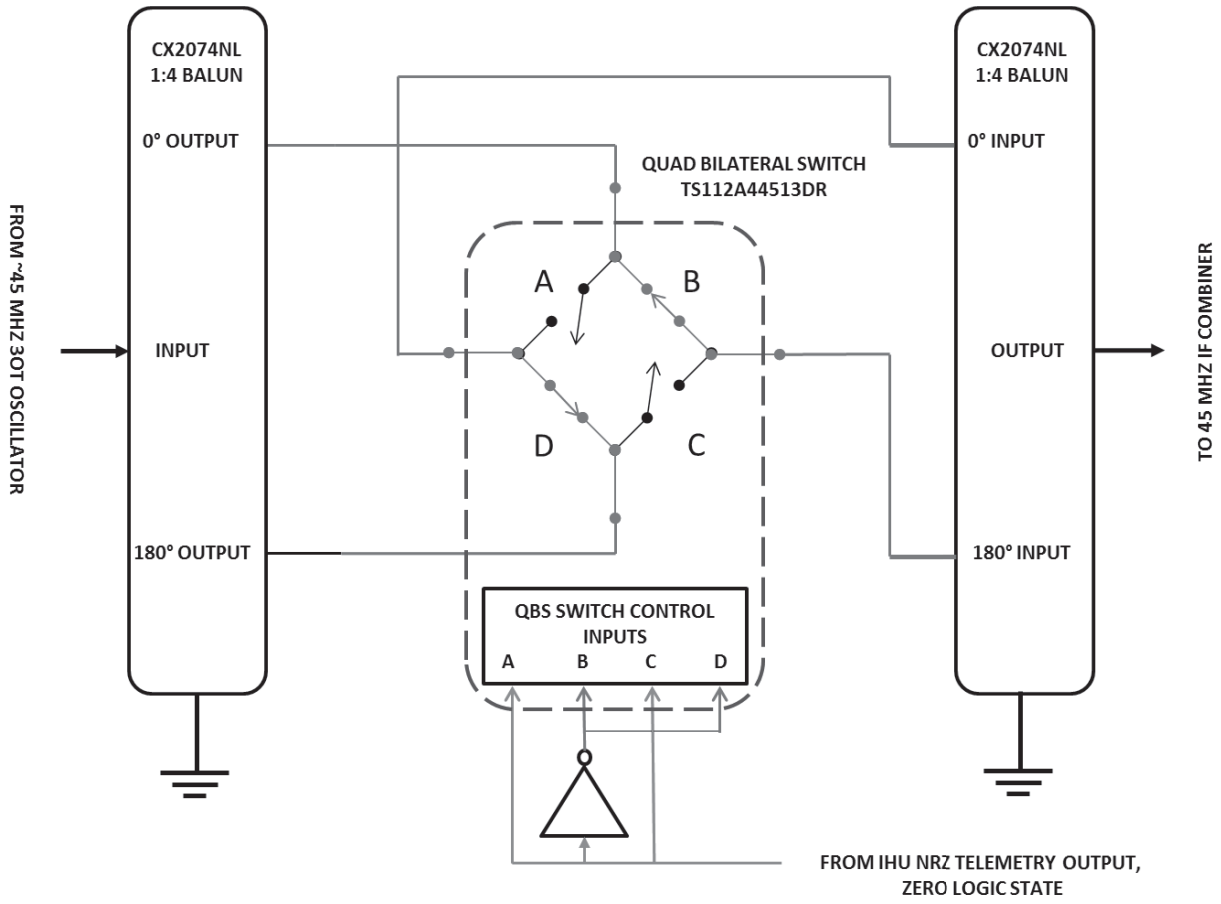
If the NRZ telemetry output of the IHU changes to the zero logic state, then switches B and D close, and A and C open, resulting in the following signal path:



In this state, the zero phase output pin from the input balun is connected to the 180 degree input pin on the output balun via switch B. Simultaneously, the 180 degree output pin on the input balun is connected to the zero degree input pin on the output balun via switch D. In this state, the RF output signal is 180 degrees out of phase with the RF input signal.

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The relative change in output phase relative to the input signal impresses the BPSK modulation on the input carrier. In the 'ONE' state, the output is in phase with the input, and in the 'ZERO' state, the output is 180 degrees out of phase with the input carrier. This resulting ~45 MHz BPSK modulated carrier can then be combined with the user transponder bandwidth, mixed up to 70 cm and further amplified by the power amplifier.

The output of this BPSK modulator would be united with the user signals with the aid of an RF combiner. The RF combiner could be in the form of a directional coupler or a 3 dB, zero degree hybrid, whichever is more appropriate to match other constraints on signal level and PCB real estate area.

The keying of the BPSK signal is not synchronous with the carrier in this approach. Synchronicity is not critical when the carrier frequency is several orders of magnitude higher than the keying rate, which it is in this case. The ratio of keyed to carrier frequency in this instance is approximately 37,500 to 1.

Summary: This approach is proposed because traditional high level double balanced diode mixers require significant power to operate due to high current level signals to make the diodes conduct to switch the RF signal. With the QBS, the signal drive levels can be quite low which is more desirable for low power satellite circuitry.

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Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Valparaiso, USA-IN
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/5),pilots

Link Input Parameters	Value	Units
Site latitude	41.47N	degrees
Site longitude	87.07W	degrees
Site altitude	0.230	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	42.3	
Availability (average year)	95.0000	%
Antenna aperture	2.4	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	52.92	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	10	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-0.30	dB
Information rate	.05	Mbps
Required Eb/No	-0.30	dB
Information rate	.05	Mbps
Overhead	0	%
FEC code rate	0.3853	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	3	dB

General Calculations	Value	Units
XPD during rain	46.83	dB
Propagation time delay	1.350932	seconds
Antenna gain	46.56	dBi
EIRP density (satellite)	-23.12	dBW/Hz
EIRP density (flange)	-204.61	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	95.1645	%
Minimum antenna size	2.3890	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.32	0.47	dB
Tropospheric scintillation	0.00	0.42	dB
Cloud attenuation	0.00	0.47	dB
Rain attenuation	0.00	0.26	dB
Total attenuation (gas-rain-cloud-scintillation)	0.32	1.31	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.72	dB
Downlink degradation (DND)	0.00	2.72	dB
Total system noise	130.70	194.35	K
Figure of merit (G/T)	25.40	23.68	dB/K
Power flux density	-158.14	-160.86	dBW/m2
Carrier power at LNB output	-133.46	-136.17	dBW
Carrier level at LNB output (75 Ohm)	5.29	2.58	dBuV
Carrier level at LNB output (75 Ohm)	-54.71	-57.42	dBmV
C/No (thermal)	53.66	50.94	dB.Hz
C/N (thermal)	5.54	2.82	dB
C/ACI	91.88	91.88	dB
C/ASI	91.88	91.88	dB
C/CCI	91.88	91.88	dB
C/IM	20.00	20.00	dB
C/(N+I)	5.39	2.74	dB
Implementation loss	0.00	0.00	dB
System margin	3.00	3.00	dB
Net Es/(No+Io)	2.39	-0.26	dB
Required Es/(No+Io)	-0.30	-0.30	dB
Excess margin	**2.69**	**0.04**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.0500	Mbps
Information rate (inc overhead)	0.0500	Mbps
Transmit rate	0.1298	Mbps
Symbol rate	0.0649	MBaud
Noise Bandwidth	48.12	dB.Hz
Occupied bandwidth	0.0779	MHz
Allocated bandwidth	0.0910	MHz

Downlink Budget

Produced by AB2S

Wednesday 8 June 2016

Service Name	lunar
Downlink earth station	Leesburg, USA-VA
Satellite name	Heimdallr
Modcod	DVBS2,short frame,BPSK-S (1/5) *,pilots

Link Input Parameters	Value	Units
Site latitude	39.12N	degrees
Site longitude	77.57W	degrees
Site altitude	0.104	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	47.7	
Availability (average year)	95.0000	%
Antenna aperture	2.0	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	44.31	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	22	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	20	degrees
Longitude Difference	20	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	2-PSK	
Required Es/No	-9.60	dB
Information rate	.005	Mbps
Required Eb/No	-9.60	dB
Information rate	.005	Mbps
Overhead	0	%
FEC code rate	0.0731	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	50.21	dB
Propagation time delay	1.350932	seconds
Antenna gain	44.98	dBi
EIRP density (satellite)	-26.35	dBW/Hz
EIRP density (flange)	-208.46	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	94.9999	%
Minimum antenna size	2.0000	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	22.00	22.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.17	0.24	dB
Tropospheric scintillation	0.00	0.20	dB
Cloud attenuation	0.00	0.33	dB
Rain attenuation	0.00	0.18	dB
Total attenuation (gas-rain-cloud-scintillation)	0.17	0.79	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.29	dB
Downlink degradation (DND)	0.00	1.90	dB
Total system noise	122.10	164.15	K
Figure of merit (G/T)	24.11	22.83	dB/K
Power flux density	-161.14	-163.04	dBW/m2
Carrier power at LNB output	-138.04	-139.94	dBW
Carrier level at LNB output (75 Ohm)	0.71	-1.19	dBuV
Carrier level at LNB output (75 Ohm)	-59.29	-61.19	dBmV
C/No (thermal)	49.52	47.62	dB.Hz
C/N (thermal)	1.17	-0.73	dB
C/ACI	91.65	91.65	dB
C/ASI	91.65	91.65	dB
C/CCI	91.65	91.65	dB
C/IM	20.00	20.00	dB
C/(N+I)	1.12	-0.77	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Es/(No+Io)	-7.88	-9.77	dB
Required Es/(No+Io)	-9.60	-9.60	dB
Excess margin	**1.72**	**-0.17**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.0050	Mbps
Information rate (inc overhead)	0.0050	Mbps
Transmit rate	0.0684	Mbps
Symbol rate	0.0684	MBaud
Noise Bandwidth	48.35	dB.Hz
Occupied bandwidth	0.0821	MHz
Allocated bandwidth	0.1000	MHz

Downlink Budget

Produced by AB2S

Wednesday 8 June 2016

Service Name	lunar
Downlink earth station	Leesburg, USA-VA
Satellite name	Heimdallr
Modcod	DVBS2,medium frame,BPSK (1/5) *,no pilots

Link Input Parameters	Value	Units
Site latitude	39.12N	degrees
Site longitude	77.57W	degrees
Site altitude	0.104	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	47.7	
Availability (average year)	95.0000	%
Antenna aperture	2.0	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	44.31	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	22	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	20	degrees
Longitude Difference	20	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	2-PSK	
Required Es/No	-6.85	dB
Information rate	.005	Mbps
Required Eb/No	-6.85	dB
Information rate	.005	Mbps
Overhead	0	%
FEC code rate	0.1677	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	50.21	dB
Propagation time delay	1.350932	seconds
Antenna gain	44.98	dBi
EIRP density (satellite)	-22.74	dBW/Hz
EIRP density (flange)	-204.86	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	97.6040	%
Minimum antenna size	1.8550	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	22.00	22.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.17	0.24	dB
Tropospheric scintillation	0.00	0.20	dB
Cloud attenuation	0.00	0.33	dB
Rain attenuation	0.00	0.18	dB
Total attenuation (gas-rain-cloud-scintillation)	0.17	0.79	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.29	dB
Downlink degradation (DND)	0.00	1.90	dB
Total system noise	122.10	164.15	K
Figure of merit (G/T)	24.11	22.83	dB/K
Power flux density	-161.14	-163.04	dBW/m2
Carrier power at LNB output	-138.04	-139.94	dBW
Carrier level at LNB output (75 Ohm)	0.71	-1.19	dBuV
Carrier level at LNB output (75 Ohm)	-59.29	-61.19	dBmV
C/No (thermal)	49.52	47.62	dB.Hz
C/N (thermal)	4.78	2.88	dB
C/ACI	95.26	95.26	dB
C/ASI	95.26	95.26	dB
C/CCI	95.26	95.26	dB
C/IM	20.00	20.00	dB
C/(N+I)	4.65	2.79	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Es/(No+Io)	-4.35	-6.21	dB
Required Es/(No+Io)	-6.85	-6.85	dB
Excess margin	**2.50**	**0.64**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.0050	Mbps
Information rate (inc overhead)	0.0050	Mbps
Transmit rate	0.0298	Mbps
Symbol rate	0.0298	MBaud
Noise Bandwidth	44.74	dB.Hz
Occupied bandwidth	0.0358	MHz
Allocated bandwidth	0.0500	MHz

Downlink Budget

Produced by AB2S

Wednesday 8 June 2016

Service Name	lunar
Downlink earth station	Leesburg, USA-VA
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/4),no pilots

Link Input Parameters	Value	Units
Site latitude	39.12N	degrees
Site longitude	77.57W	degrees
Site altitude	0.104	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	47.7	
Availability (average year)	95.0000	%
Antenna aperture	2.0	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	44.31	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	22	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	20	degrees
Longitude Difference	20	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-2.35	dB
Information rate	.005	Mbps
Required Eb/No	-2.35	dB
Information rate	.005	Mbps
Overhead	0	%
FEC code rate	0.2451	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	50.21	dB
Propagation time delay	1.350932	seconds
Antenna gain	44.98	dBi
EIRP density (satellite)	-18.09	dBW/Hz
EIRP density (flange)	-200.20	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	97.6654	%
Minimum antenna size	1.8500	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	22.00	22.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.17	0.24	dB
Tropospheric scintillation	0.00	0.20	dB
Cloud attenuation	0.00	0.33	dB
Rain attenuation	0.00	0.18	dB
Total attenuation (gas-rain-cloud-scintillation)	0.17	0.79	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.29	dB
Downlink degradation (DND)	0.00	1.90	dB
Total system noise	122.10	164.15	K
Figure of merit (G/T)	24.11	22.83	dB/K
Power flux density	-161.14	-163.04	dBW/m2
Carrier power at LNB output	-138.04	-139.94	dBW
Carrier level at LNB output (75 Ohm)	0.71	-1.19	dBuV
Carrier level at LNB output (75 Ohm)	-59.29	-61.19	dBmV
C/No (thermal)	49.52	47.62	dB.Hz
C/N (thermal)	9.44	7.53	dB
C/ACI	99.91	99.91	dB
C/ASI	99.91	99.91	dB
C/CCI	99.91	99.91	dB
C/IM	20.00	20.00	dB
C/(N+I)	9.07	7.29	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Es/(No+Io)	0.07	-1.71	dB
Required Es/(No+Io)	-2.35	-2.35	dB
Excess margin	**2.42**	**0.64**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.0050	Mbps
Information rate (inc overhead)	0.0050	Mbps
Transmit rate	0.0204	Mbps
Symbol rate	0.0102	MBaud
Noise Bandwidth	40.09	dB.Hz
Occupied bandwidth	0.0122	MHz
Allocated bandwidth	0.0200	MHz

Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Perth, Australia
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/5),no pilots

Link Input Parameters	Value	Units
Site latitude	31.97S	degrees
Site longitude	115.82E	degrees
Site altitude	0.100	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	39.8	
Availability (average year)	95.0000	%
Antenna aperture	7.6	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	54.18	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-0.30	dB
Information rate	.6	Mbps
Required Eb/No	-0.30	dB
Information rate	.6	Mbps
Overhead	0	%
FEC code rate	0.3947	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	3	dB

General Calculations	Value	Units
XPD during rain	47.99	dB
Propagation time delay	1.350932	seconds
Antenna gain	56.58	dBi
EIRP density (satellite)	-33.81	dBW/Hz
EIRP density (flange)	-204.46	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	95.7389	%
Minimum antenna size	7.4690	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.33	0.39	dB
Tropospheric scintillation	0.00	0.44	dB
Cloud attenuation	0.00	0.15	dB
Rain attenuation	0.00	0.22	dB
Total attenuation (gas-rain-cloud-scintillation)	0.33	0.97	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.24	dB
Downlink degradation (DND)	0.00	1.87	dB
Total system noise	131.97	175.55	K
Figure of merit (G/T)	35.37	34.13	dB/K
Power flux density	-158.14	-160.01	dBW/m2
Carrier power at LNB output	-123.44	-125.32	dBW
Carrier level at LNB output (75 Ohm)	15.31	13.43	dBuV
Carrier level at LNB output (75 Ohm)	-44.69	-46.57	dBmV
C/No (thermal)	63.62	61.74	dB.Hz
C/N (thermal)	4.81	2.93	dB
C/ACI	81.19	81.19	dB
C/ASI	81.19	81.19	dB
C/CCI	81.19	81.19	dB
C/IM	20.00	20.00	dB
C/(N+I)	4.68	2.85	dB
Implementation loss	0.00	0.00	dB
System margin	3.00	3.00	dB
Net Es/(No+Io)	1.68	-0.15	dB
Required Es/(No+Io)	-0.30	-0.30	dB
Excess margin	**1.98**	**0.15**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.6000	Mbps
Information rate (inc overhead)	0.6000	Mbps
Transmit rate	1.5201	Mbps
Symbol rate	0.7601	MBaud
Noise Bandwidth	58.81	dB.Hz
Occupied bandwidth	0.9121	MHz
Allocated bandwidth	1.0700	MHz

Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Bochum, Germany
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/5),no pilots

Link Input Parameters	Value	Units
Site latitude	51.47N	degrees
Site longitude	7.18E	degrees
Site altitude	0.122	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	37.4	
Availability (average year)	95.0000	%
Antenna aperture	21	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	53.53	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	10	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-0.30	dB
Information rate	4.5	Mbps
Required Eb/No	-0.30	dB
Information rate	4.5	Mbps
Overhead	0	%
FEC code rate	0.3947	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	3	dB

General Calculations	Value	Units
XPD during rain	49.45	dB
Propagation time delay	1.350932	seconds
Antenna gain	65.40	dBi
EIRP density (satellite)	-42.56	dBW/Hz
EIRP density (flange)	-204.68	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	94.9999	%
Minimum antenna size	21.0000	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.33	0.40	dB
Tropospheric scintillation	0.00	0.22	dB
Cloud attenuation	0.00	0.40	dB
Rain attenuation	0.00	0.18	dB
Total attenuation (gas-rain-cloud-scintillation)	0.33	1.03	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.48	dB
Downlink degradation (DND)	0.00	2.18	dB
Total system noise	131.32	184.76	K
Figure of merit (G/T)	44.22	42.74	dB/K
Power flux density	-158.14	-160.32	dBW/m2
Carrier power at LNB output	-114.62	-116.79	dBW
Carrier level at LNB output (75 Ohm)	24.13	21.96	dBuV
Carrier level at LNB output (75 Ohm)	-35.87	-38.04	dBmV
C/No (thermal)	72.47	70.29	dB.Hz
C/N (thermal)	4.91	2.73	dB
C/ACI	72.44	72.44	dB
C/ASI	72.44	72.44	dB
C/CCI	72.44	72.44	dB
C/IM	20.00	20.00	dB
C/(N+I)	4.78	2.65	dB
Implementation loss	0.00	0.00	dB
System margin	3.00	3.00	dB
Net Es/(No+Io)	1.78	-0.35	dB
Required Es/(No+Io)	-0.30	-0.30	dB
Excess margin	**2.08**	**-0.05**	**dB**

Space Segment Utilization	Value	Units
Information rate	4.5000	Mbps
Information rate (inc overhead)	4.5000	Mbps
Transmit rate	11.4011	Mbps
Symbol rate	5.7005	MBaud
Noise Bandwidth	67.56	dB.Hz
Occupied bandwidth	6.8406	MHz
Allocated bandwidth	7.9900	MHz

Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Valparaiso, USA-IN
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/3),pilots

Link Input Parameters	Value	Units
Site latitude	41.47N	degrees
Site longitude	87.07W	degrees
Site altitude	0.230	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	42.3	
Availability (average year)	95.0000	%
Antenna aperture	4.2	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	52.92	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	10	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-1.24	dB
Information rate	.16	Mbps
Required Eb/No	-1.24	dB
Information rate	.16	Mbps
Overhead	0	%
FEC code rate	0.3204	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	3	dB

General Calculations	Value	Units
XPD during rain	46.83	dB
Propagation time delay	1.350932	seconds
Antenna gain	51.42	dBi
EIRP density (satellite)	-28.97	dBW/Hz
EIRP density (flange)	-205.60	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	95.0614	%
Minimum antenna size	4.1930	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.32	0.47	dB
Tropospheric scintillation	0.00	0.40	dB
Cloud attenuation	0.00	0.47	dB
Rain attenuation	0.00	0.26	dB
Total attenuation (gas-rain-cloud-scintillation)	0.32	1.30	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.72	dB
Downlink degradation (DND)	0.00	2.71	dB
Total system noise	130.70	194.35	K
Figure of merit (G/T)	30.26	28.54	dB/K
Power flux density	-158.14	-160.85	dBW/m2
Carrier power at LNB output	-128.60	-131.30	dBW
Carrier level at LNB output (75 Ohm)	10.15	7.45	dBuV
Carrier level at LNB output (75 Ohm)	-49.85	-52.55	dBmV
C/No (thermal)	58.52	55.81	dB.Hz
C/N (thermal)	4.55	1.84	dB
C/ACI	86.03	86.03	dB
C/ASI	86.03	86.03	dB
C/CCI	86.03	86.03	dB
C/IM	20.00	20.00	dB
C/(N+I)	4.42	1.77	dB
Implementation loss	0.00	0.00	dB
System margin	3.00	3.00	dB
Net Es/(No+Io)	1.42	-1.23	dB
Required Es/(No+Io)	-1.24	-1.24	dB
Excess margin	**2.66**	**0.01**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.1600	Mbps
Information rate (inc overhead)	0.1600	Mbps
Transmit rate	0.4994	Mbps
Symbol rate	0.2497	MBaud
Noise Bandwidth	53.97	dB.Hz
Occupied bandwidth	0.2996	MHz
Allocated bandwidth	0.3500	MHz

Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Perth, Australia
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/3),no pilots

Link Input Parameters	Value	Units
Site latitude	31.97S	degrees
Site longitude	115.82E	degrees
Site altitude	0.100	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	39.8	
Availability (average year)	95.0000	%
Antenna aperture	7.6	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	54.18	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-1.24	dB
Information rate	.15	Mbps
Required Eb/No	-1.24	dB
Information rate	.15	Mbps
Overhead	0	%
FEC code rate	0.3282	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	47.99	dB
Propagation time delay	1.350932	seconds
Antenna gain	56.58	dBi
EIRP density (satellite)	-28.59	dBW/Hz
EIRP density (flange)	-199.24	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	95.6213	%
Minimum antenna size	7.4910	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.33	0.39	dB
Tropospheric scintillation	0.00	0.44	dB
Cloud attenuation	0.00	0.15	dB
Rain attenuation	0.00	0.22	dB
Total attenuation (gas-rain-cloud-scintillation)	0.33	0.97	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.24	dB
Downlink degradation (DND)	0.00	1.87	dB
Total system noise	131.97	175.55	K
Figure of merit (G/T)	35.37	34.13	dB/K
Power flux density	-158.14	-160.01	dBW/m2
Carrier power at LNB output	-123.44	-125.32	dBW
Carrier level at LNB output (75 Ohm)	15.31	13.43	dBuV
Carrier level at LNB output (75 Ohm)	-44.69	-46.57	dBmV
C/No (thermal)	63.62	61.74	dB.Hz
C/N (thermal)	10.03	8.15	dB
C/ACI	86.41	86.41	dB
C/ASI	86.41	86.41	dB
C/CCI	86.41	86.41	dB
C/IM	20.00	20.00	dB
C/(N+I)	9.61	7.88	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Es/(No+Io)	0.61	-1.12	dB
Required Es/(No+Io)	-1.24	-1.24	dB
Excess margin	**1.85**	**0.12**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.1500	Mbps
Information rate (inc overhead)	0.1500	Mbps
Transmit rate	0.4570	Mbps
Symbol rate	0.2285	MBaud
Noise Bandwidth	53.59	dB.Hz
Occupied bandwidth	0.2742	MHz
Allocated bandwidth	0.3200	MHz

Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Bochum, Germany
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/3),no pilots

Link Input Parameters	Value	Units
Site latitude	51.47N	degrees
Site longitude	7.18E	degrees
Site altitude	0.122	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	37.4	
Availability (average year)	95.0000	%
Antenna aperture	21	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	53.53	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-1.24	dB
Information rate	1.1	Mbps
Required Eb/No	-1.24	dB
Information rate	1.1	Mbps
Overhead	0	%
FEC code rate	0.3282	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	49.45	dB
Propagation time delay	1.350932	seconds
Antenna gain	65.40	dBi
EIRP density (satellite)	-37.24	dBW/Hz
EIRP density (flange)	-199.37	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	95.1267	%
Minimum antenna size	20.9490	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.33	0.40	dB
Tropospheric scintillation	0.00	0.22	dB
Cloud attenuation	0.00	0.40	dB
Rain attenuation	0.00	0.18	dB
Total attenuation (gas-rain-cloud-scintillation)	0.33	1.03	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.48	dB
Downlink degradation (DND)	0.00	2.18	dB
Total system noise	131.32	184.76	K
Figure of merit (G/T)	44.22	42.74	dB/K
Power flux density	-158.14	-160.32	dBW/m2
Carrier power at LNB output	-114.62	-116.79	dBW
Carrier level at LNB output (75 Ohm)	24.13	21.96	dBuV
Carrier level at LNB output (75 Ohm)	-35.87	-38.04	dBmV
C/No (thermal)	72.47	70.29	dB.Hz
C/N (thermal)	10.22	8.05	dB
C/ACI	77.76	77.76	dB
C/ASI	77.76	77.76	dB
C/CCI	77.76	77.76	dB
C/IM	20.00	20.00	dB
C/(N+I)	9.79	7.78	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Es/(No+Io)	0.79	-1.22	dB
Required Es/(No+Io)	-1.24	-1.24	dB
Excess margin	**2.03**	**0.02**	**dB**

Space Segment Utilization	Value	Units
Information rate	1.1000	Mbps
Information rate (inc overhead)	1.1000	Mbps
Transmit rate	3.3516	Mbps
Symbol rate	1.6758	MBaud
Noise Bandwidth	62.24	dB.Hz
Occupied bandwidth	2.0110	MHz
Allocated bandwidth	2.3500	MHz

Downlink Budget

Produced by AB2S

Wednesday 15 June 2016

Service Name	lunar
Downlink earth station	Valparaiso, USA-IN
Satellite name	Heimdallr
Modcod	DVBS2,normal frame,4-PSK (1/3),no pilots

Link Input Parameters	Value	Units
Site latitude	41.47N	degrees
Site longitude	87.07W	degrees
Site altitude	0.230	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	42.3	
Availability (average year)	95.0000	%
Antenna aperture	4.2	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	52.92	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	25	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	10	degrees
Longitude Difference	10	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	4-PSK	
Required Es/No	-1.24	dB
Information rate	.035	Mbps
Required Eb/No	-1.24	dB
Information rate	.035	Mbps
Overhead	0	%
FEC code rate	0.3282	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	46.83	dB
Propagation time delay	1.350932	seconds
Antenna gain	51.42	dBi
EIRP density (satellite)	-22.27	dBW/Hz
EIRP density (flange)	-198.89	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	96.6888	%
Minimum antenna size	3.9570	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	25.00	25.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.32	0.47	dB
Tropospheric scintillation	0.00	0.40	dB
Cloud attenuation	0.00	0.47	dB
Rain attenuation	0.00	0.26	dB
Total attenuation (gas-rain-cloud-scintillation)	0.32	1.30	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.72	dB
Downlink degradation (DND)	0.00	2.71	dB
Total system noise	130.70	194.35	K
Figure of merit (G/T)	30.26	28.54	dB/K
Power flux density	-158.14	-160.85	dBW/m2
Carrier power at LNB output	-128.60	-131.30	dBW
Carrier level at LNB output (75 Ohm)	10.15	7.45	dBuV
Carrier level at LNB output (75 Ohm)	-49.85	-52.55	dBmV
C/No (thermal)	58.52	55.81	dB.Hz
C/N (thermal)	11.25	8.55	dB
C/ACI	92.73	92.73	dB
C/ASI	92.73	92.73	dB
C/CCI	92.73	92.73	dB
C/IM	20.00	20.00	dB
C/(N+I)	10.71	8.25	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Es/(No+Io)	1.71	-0.75	dB
Required Es/(No+Io)	-1.24	-1.24	dB
Excess margin	**2.95**	**0.49**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.0350	Mbps
Information rate (inc overhead)	0.0350	Mbps
Transmit rate	0.1066	Mbps
Symbol rate	0.0533	MBaud
Noise Bandwidth	47.27	dB.Hz
Occupied bandwidth	0.0640	MHz
Allocated bandwidth	0.0800	MHz

Downlink Budget

Produced by AB2S

Wednesday 8 June 2016

Service Name	lunar
Downlink earth station	Leesburg, USA-VA
Satellite name	Heimdallr
Modcod	Manual

Link Input Parameters	Value	Units
Site latitude	39.12N	degrees
Site longitude	77.57W	degrees
Site altitude	0.104	km
Frequency	10.5	GHz
Polarization	Vertical	
Rain model	ITU-R	
Rain zone or mm/h	47.7	
Availability (average year)	95.0000	%
Antenna aperture	1.0	metres
Antenna efficiency or gain (+ or - prefix)	65	% or dBi
Coupling loss	0	dB
Antenna mispoint loss	0	dB
Other path losses	0	dB
LNB noise figure or temp (+ prefix)	1	dB or K
Antenna noise	44.31	K
LNB gain	20	dB
LNB load impedance	75	Ohms
Csat/ACIo	140	dB/Hz
Csat/ASIo	140	dB/Hz
Csat/CCIo	140	dB/Hz
C/IM	20	dB

Satellite Input Parameters	Value	Units
EIRP (saturation)	22	dBW
Bandwidth	7	MHz
Range	405000	km
Elevation	20	degrees
Longitude Difference	20	degrees

Carrier/Link Input Parameters	Value	Units
Modulation	1 bit/symbol	
Required Eb/No	10	dB
Information rate	.00001	Mbps
Required Eb/No	10	dB
Information rate	.00001	Mbps
Overhead	0	%
FEC code rate	0.2451	
Spreading gain	0	dB
Implementation loss	0	dB
System margin	9	dB

General Calculations	Value	Units
XPD during rain	50.21	dB
Propagation time delay	1.350932	seconds
Antenna gain	38.96	dBi
EIRP density (satellite)	5.89	dBW/Hz
EIRP density (flange)	-182.24	dBW/Hz
Availability (average year)	95.0000	%
Link downtime (average year)	438.300	hours
Availability (worst month)	88.4386	%
Link downtime (worst month)	84.456	hours
Maximum availability	99.9901	%
Minimum antenna size	0.2610	metres

Downlink Calculation	Clear	Rain	Units
Satellite EIRP per carrier	22.00	22.00	dBW
Antenna mispoint	0.00	0.00	dB
Free space loss	225.02	225.02	dB
Atmospheric absorption	0.17	0.24	dB
Tropospheric scintillation	0.00	0.20	dB
Cloud attenuation	0.00	0.33	dB
Rain attenuation	0.00	0.18	dB
Total attenuation (gas-rain-cloud-scintillation)	0.17	0.79	dB
Other path losses	0.00	0.00	dB
Noise increase due to precipitation	0.00	1.29	dB
Downlink degradation (DND)	0.00	1.90	dB
Total system noise	122.10	164.15	K
Figure of merit (G/T)	18.09	16.81	dB/K
Power flux density	-161.14	-163.05	dBW/m2
Carrier power at LNB output	-144.06	-145.97	dBW
Carrier level at LNB output (75 Ohm)	-5.31	-7.21	dBuV
Carrier level at LNB output (75 Ohm)	-65.31	-67.21	dBmV
C/No (thermal)	43.50	41.60	dB.Hz
C/N (thermal)	27.40	25.49	dB
C/ACI	123.89	123.89	dB
C/ASI	123.89	123.89	dB
C/CCI	123.89	123.89	dB
C/IM	20.00	20.00	dB
C/(N+I)	19.27	18.92	dB
Eb/(No+Io)	25.38	25.03	dB
Implementation loss	0.00	0.00	dB
System margin	9.00	9.00	dB
Net Eb/(No+Io)	16.38	16.03	dB
Required Eb/(No+Io)	10.00	10.00	dB
Excess margin	**6.38**	**6.03**	**dB**

Space Segment Utilization	Value	Units
Information rate	0.0000	Mbps
Information rate (inc overhead)	0.0000	Mbps
Transmit rate	0.0000	Mbps
Symbol rate	0.0000	MBaud
Noise Bandwidth	16.11	dB.Hz
Occupied bandwidth	0.0000	MHz
Allocated bandwidth	0.0100	MHz